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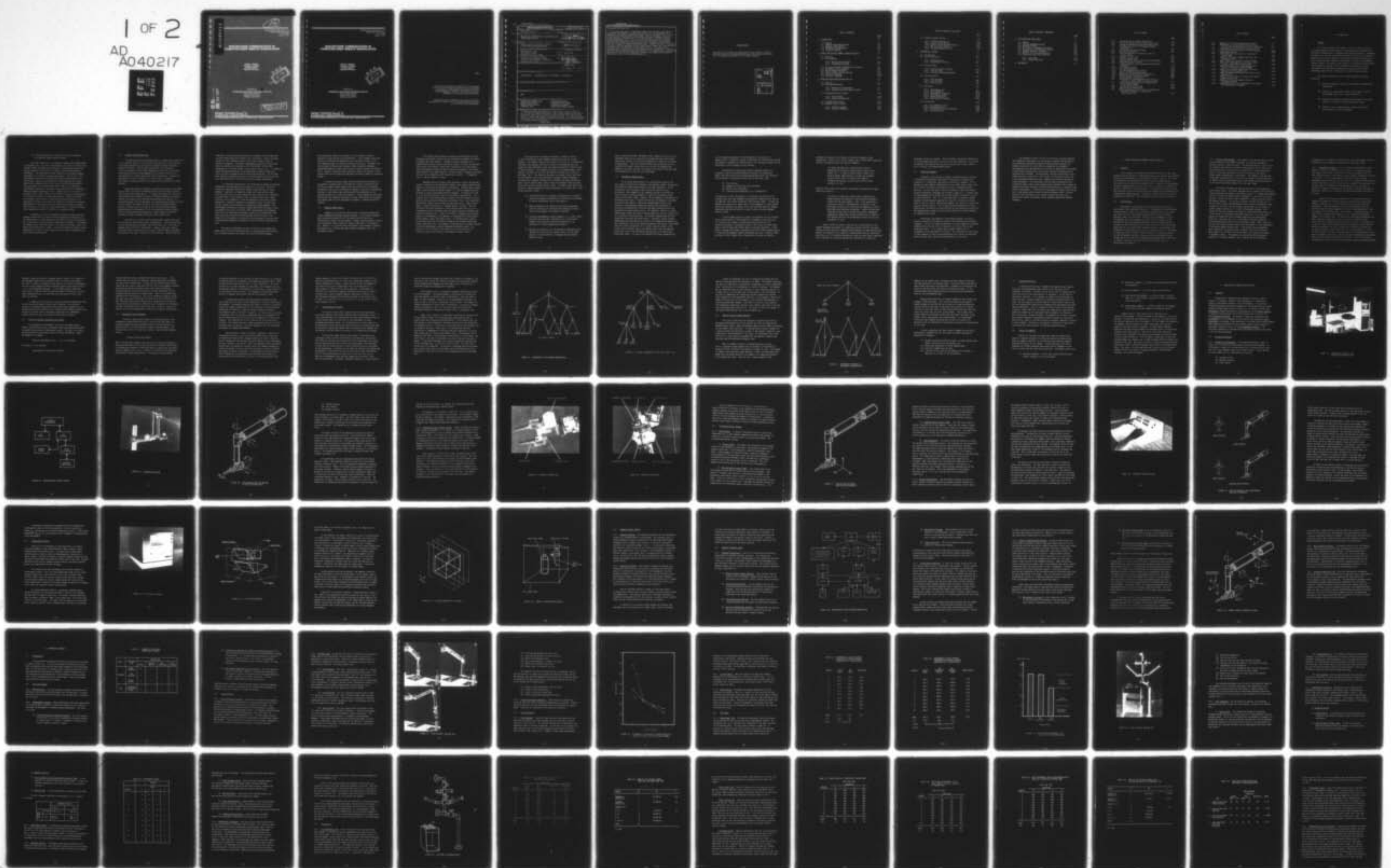

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MAN-MACHINE COMMUNICATION IN COMPUTER-AIDED REMOTE MANIPULATION

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Prepared For:

ENGINEERING PSYCHOLOGY PROGRAMS (CODE 455)
Office of Naval Research
Department of the Navy
Arlington, Virginia 22217

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Automated Remote Manipulation is both an area of great practical utility for Navy Undersea Operations, and a prime example of new type of man-machine interaction in which the human operator must supervise and control a complex and adaptive man-computer system. This report presents the results of an experimental study focusing on man-machine communication with computer-aided manipulators.

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This report describes (1) underwater manipulator functions and operator performance requirements in remote manipulation, (2) the development of a theoretical man-machine communication model based on procedural sets, and (3) an experimental investigation on the effect of several elementary computer aiding techniques on the ability of trained operators to perform selected remote manipulation tasks. The results of the experimental investigation indicated that computer aiding can significantly decrease task performance times for a number of remote manipulation tasks. Computer aiding in the form of resolved motion and automated control significantly reduced the times required to perform valve turning and ring manipulation tasks. The results also indicated that if higher-level aiding schemes are to be effective in terms of improving man-machine performance, the design of the communications language and interface must be carefully designed to maintain the communication goals of naturalness, simplicity and understandability.

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1. INTRODUCTION

1.1 Summary

This report describes the results of the first year's effort in a research program directed toward the investigation and optimization of man-machine communication in computer-aided remote manipulation. Automated manipulation is both an area of great practical utility for Navy undersea operations, and a prime example of a new type of man-machine symbiosis, in which a human operator supervises and controls a complex, semiautonomous computer system. The intent of this program is to determine experimentally the relationships between critical communication factors and system performance, and to develop and demonstrate a communication design methodology applicable to a broad class of remotely manned systems.

The specific objectives of the research program include the following:

(1) Perform a theoretical analysis of man-machine communication requirements.

(2) Establish an experimental system for the study of shared man-computer control of a remote manipulator.

(3) Implement and evaluate communications systems for efficient control of a variety of remote manipulation tasks.

(4) Identify critical communications factors and establish relationships to system performance.

(5) Provide guidelines for the design of future autonomous and adaptive remotely-manned systems.

This year's effort has (1) produced a communications model based on procedural nets, (2) studied experimentally the effect of several basic computer aiding techniques on performance of remote manipulation tasks, and (3) examined a preliminary test battery for predicting operator performance. The communications model identified the command language requirements for controlling remote manipulators. The results of the experimental investigation indicated that computer-aided control can significantly improve the performance of remote manipulation systems. Specifically, computer aiding in the form of real-time transformation from joint-angle to resolved motion control (RMC) of the end-point significantly reduced the time required and number of errors committed in performing remote manipulation tasks. Computer aiding in the form of automatic motion control (AMC) to specifiable locations also demonstrated its potential usefulness in remote manipulation. However, performance with automatic motion control indicated that improved design of the man-machine interface is necessary for effective utilization of computer-aided control. The results of the preliminary test battery indicated that the ability to visualize 3-dimensional objects is highly correlated with a manipulator operator's ability to use computer aiding.

In summary, this year's experimental program has shown that basic computer-aided control can improve remote manipulator performance, but the effectiveness of aiding depends on the characteristics of the operator and on the design of the man-machine communication interface. Accordingly, the communications interface becomes a significant performance factor for shared-control manipulator systems. Future utilization of advanced aiding techniques will require careful attention to the control language and to human factors considerations.

1.2 Computer Aided Manipulation

Although men have been developing tools to extend their capabilities from prehistoric times, it is only within the past thirty years that men have created manipulative tools which are general purpose, dexterous, cybernetic machines. Called remote manipulators or teleoperators (Corliss and Johnson, 1967), these manipulative tools are distinct from other machines which are preprogrammed to do a specific task with no considerations of closed loop control, human intervention, or dexterity. Manipulators are able to perform a variety of tasks in changing environments by remaining under close supervision and control of a human operator.

Remote manipulators allow man to extend the functions of the human arm and hand into hostile environments where he himself cannot function. These devices have allowed man to: (1) sample and examine the surface of other planets while remaining on earth; (2) handle dangerous or explosive chemicals and objects while stationed behind protective barriers; (3) manipulate nuclear fuel and equipment in a radioactive environment; (4) lift ton-size loads; (5) replace the use of lost limbs through prosthetic devices; (6) handle parts on assembly lines for long periods without becoming bored or error-prone; (7) pick up, examine or recover objects from the ocean bottom while remaining in a deep submersible; and (8) construct or repair underwater pipelines from a surface ship.

Historically, two basic types of manipulators, master-slave and rate controlled, have found the most widespread use. These two types may use the same manipulator hardware; their difference lies in the form of command inputs required of the operator. However, both types require continuous control inputs and direct visual or force feedback throughout the execution of a task. Therein lie the limitations. Master-slave and

continuous rate-controlled manipulators are extremely slow in comparison to direct human capabilities (Pesch, Hill, and Klepser, 1970); thus human control not only consumes valuable time but also severely taxes an operator's attention. Attention is demanded particularly in those cases where the operator must overcome built-in manipulator deficiencies (inadequate or no tactile sensors, high inertial forces, etc.). In addition, general-purpose manipulators are often applied to routine, repetitive tasks, but have no capabilities for error-free repetitions. On the other hand, machines designed for one job or a limited variety of jobs lack the very characteristics of flexibility desired in remote manipulators.

For underwater manipulation, the limitations of manually controlled manipulators are compounded by the problems of visibility. Control of present-day underwater manipulators depends almost entirely on visual feedback. Experience in laboratory studies and field work has shown that such devices are virtually impossible to use when vision is degraded by turbid water, by poor angle of view, by light failure, etc. These conditions occur frequently in deep sea operations, particularly during bottom work. Expedient completion of underwater tasks, for other than the most simple and most amenable to manipulator accomplishment, is an acknowledged shortcoming of present systems (Rechnitzer and Sutter, 1973). For example, Pesch, Hill, and Allen (1971) investigated the performance capabilities of underwater manipulator systems, and concluded that "the tasks which were successfully performed were more the result of the ingenuity of the operator utilizing the existing hardware, than the result of the hardware augmenting the operator's basic abilities to perform the task".

One means to compensate for poor visibility is to exchange the common switch-controlled manipulator used in many underwater applications for a bilateral master-slave system with force-reflective feedback.

Force-reflection allows the operator to "feel" through his master controller forces exerted by the manipulator. Force feedback allows the operator to know when the manipulator has contacted an object, or to tell something about its shape by following its outline. Personnel from the CEA group in France have produced a force-reflective underwater manipulator modeled on those used in atomics handling (Vertut and Charles, 1975). However, the master-slave controller retains the operator in the control loop with the previously-mentioned limitations imposed by attention demands.

A second alternative toward improving manipulator performance is to augment or automate most of the operator's control responsibilities. Corliss and Johnson (1968) suggest that the difficulties in performing manipulation tasks can be attributed to improper allocation of man-machine functions. With master-slave and rate-controlled manipulators, the operator performs all of the tasks manually. A more appropriate allocation would retain the favorable attributes of human intelligence and foresight, and combine these with the advantages of automatic, computer-controlled operation.

1.3 Computer Aided Control

Computers can be used at various levels of control ranging from control augmentation through complete autonomy. In the totally automatic mode the machine performs all of the required activities with no intervention or control by the operator. Efforts have been made to achieve fully autonomous robots, notably by Minsky (1966) and his colleagues at MIT. However, it is unlikely that intelligent, fully-automatic, deep-sea manipulators will displace the human operator completely within the foreseeable future.

The "middle ground" between the manually-operated and the fully-autonomous manipulator includes various techniques of computer-assistance to augment the human operator. Encompassing many techniques, this middle ground has been termed "supervisory control" (Ferrell and Sheridan, 1967) because the operator "supervises" the operation of a manipulator, selecting automatic functions where available and expedient, or assuming direct manual control when required. Two basic types of computer-assistance function can be identified within supervisory control: (1) augmented control, and (2) automatic control.

Augmented control includes those techniques in which the operator remains in control of the manipulator; however, the computer performs some function to facilitate the operator's performance. Resolved motion control (RMC), first described by Whitney (1969), is a form of augmented control designed to obtain coordinated end-point movement. The objective of RMC is to relieve the operator of part of the control responsibility. For example, most of the current control systems in use by the Navy are joint-by-joint rate controllers (Rechnitzer and Sutter, 1973). Rate controlled manipulators usually have one motor to power each joint. Power to each motor is usually controlled by a separate button or switch. The main limitation with rate controllers is that several motors have to be run simultaneously and at different rates to produce end-point movement along a natural coordinate (e.g., "move to the left"). Whenever more than two motors run simultaneously, the operator is presented with a heavy mental burden (Zadaca, Lyman, and Freedy, 1974). In resolved motion control, the operator specifies direction and speed of the end-point along some natural coordinate axis. The computer calculates the joint angles required to move the manipulator along the commanded coordinate system. The operator is thus relieved of the tedious and time consuming task of controlling several joint motors simultaneously (Mullen, 1973).

The second form of computer-assistance is automatic control, in which the computer assumes command responsibility for one or more subtasks. The computer executes the subtask with little or no intervention required by the operator and returns control to the operator when the subtask has been completed or when the computer encounters difficulty that it cannot overcome. Such automatic subtasks can be preprogrammed or the computer can learn the task from the operator (Freedy, Hull, Lucaccini, and Lyman, 1971). The automatic functions can proceed "blind" once they are initiated or they can be equipped to respond to sensory feedback, including force feedback (Groome, 1973; and Woodin, Whitney, and Nevins, 1973), tactile sensing (Goto, 1972), force grip feedback (Ueda and Iwata, 1973), and proximity sensing (Bejczy, 1974). In summary, the computer can be used to improve manipulator system effectiveness in several ways. Such aiding functions include:

(1) Performing difficult coordinate transformations to simplify operator performance requirements in controlling the movement of several manipulator joints simultaneously.

(2) Reducing operator task loading by providing the operator with the capability of allocating task elements or entire tasks to the computer for automatic completion.

(3) Providing supplementary sensory feedback (i.e., force, touch, processed real-time task information, etc.) which would enhance system monitoring and allow operations to be completed in visually degraded environments.

(4) Reducing the probability of the manipulator damaging itself, through collisions with the support vehicle or with other objects in the environment, by remembering and avoiding dangerous areas.

Nevins, Sheridan, Whitney, and Woodin (1973) suggest that until a fully autonomous robot can be successfully developed and used, multi-moded supervisory systems will be most advantageous for effective utilization of manipulators. Such multi-moded systems would include not only the capability for manual control but also a variety of augmented and automatic functions from which the operator can select the control mode most appropriate for the task to be performed.

1.4 Man-Machine Communication

As we extend shared control of a manipulation system to the full range of capabilities afforded by the computer element, the question of man-machine communication becomes of primary importance. In any manipulation task the operator must observe the actions of the manipulator, make judgments of the commands necessary to perform the task, and carry out those judgments in terms of manipulator control (Corliss and Johnson, 1968). However, the involvement of the operator in performing these tasks is strongly affected by the degree of assistance provided by the computer. When using unaided manual control, the question of communication between the operator and the machine is relatively straightforward, involving continuous operator control and observation of every machine action. The operator's control is usually communicated through some form of analog controller, such as a master arm or a position or rate controller. The operator communicates with the manipulator by moving the control device. Certainly, control becomes complicated when constraints are placed on the communication between the man and machine, such as time delays, bandwidth restrictions, insufficient room for a master controller, etc. However, the man remains in the control loop, retaining direct, continuous control over the machine's activities, albeit with performance degradations as the constraints become more severe. As long as the operator has direct responsibility

for all elementary movements of the manipulator, the question of communication is primarily a matter of optimizing the relationships between the operator's movement of a control device, the subsequent movement of the manipulator, and the feedback to the operator.

Introduction of supervisory control techniques changes the character of the relationship between the operator and manipulator. Rather than controlling directly every manipulator action, the functions of the operator in supervisory control are to (Sheridan, 1975):

(1) Plan the task
(2) Communicate (initialize task operation)
(3) Monitor task performance
(4) Intervene when appropriate (i.e., emergencies)

In supervisory control the operator is relieved of the need to close constantly the real time feedback loop around the remote effector (Bejczy and Johnston, 1974; Janow and Malone, 1973; Whitney, 1968). Instead, the operator can control at a higher level, giving commands of a more general nature and relying on the remote unit to do sufficient sensing, feedback processing, and decision making in order to carry out those commands (Ferrell, 1973).

In multi-moded supervisory control the operator not only provides direct analog control of the manipulator's movements, but he must also (1) select any of a number of computer-assistance functions, (2) monitor the progress of automated routines, (3) be able to resume manual control, and (4) know what control mode is currently operating. A wide range of communication modes, encompassing more than simple analog control, is required when augmented remote manipulators are used. Verplank (1966) and Ferrell (1973) suggest that a combination of analog and symbolic

commands are required for effective utilization of computer-aided manipulators. Nevins, et al (1973), suggest that in multi-moded supervisory control, the operator gives two types of commands:

> "(1) Object designations, accomplished by moving or commanding the motions of some surveying system at the remote site . . .; [and] (2) motion plans, ranging from detailed manual specifications of actual arm movements using a control stick, to higher level symbolic statements describing a task or calling forth stored routines" (p. 175).

McGovern (1974) states with regard to the problem of communication under supervisory control:

> "The effect of requiring a wider range of communication between operator and computer on the selected performance criteria has not been studied. That is, the usefulness of supervisory control is determined by a reduction in some performance criteria or by provision for completion of tasks which would not otherwise be possible. Studies to date have simulated various parts of systems and various rudimentary augmentation capabilities but the interaction of a number of such capabilities with the performance criteria has not been considered" (p. 200).

Ferrell (1973) has given a clear and concise description of the command language requirements for supervisory control and Hill and Sword (1973a and 1973b) describe a computer-based language for remote manipulation. However, the question of the operator's communication with the supervisory controller as he is performing manipulation tasks has been largely undefined. Thus, a designer of a specific man-machine interface has virtually no

guidelines on which to proceed. For the automatic and manual capabilities of a multi-moded supervisory controller to be fully effective in assisting an operator, the operator must be able to request them simply, rapidly, and in a natural and understandable manner.

1.5 Technical Approach

According to the concept of computer-aided manipulation outlined in the previous paragraphs, the problem of designing a communications interface is, in many ways, equivalent to designing a language. Yet as important as man-computer communications are to human factors today, there are virtually no guidelines available for such a "language building" activity. In fact, the recent history of attempts to construct general-purpose technological languages has not been a happy one. It appears that our understanding of the formal and informal nature of language is not up to that undertaking. Thus it is overly ambitious to consider a general language for man-computer communication, despite its attractive nature. Within a specific area of application, however, the chances for significant progress are much greater. This is because actual mechanisms and tasks place natural constraints on the primitives and transformations required of the communications scheme, and also provide empirically-defined measures of communications success.

Accordingly, the approach in the present program is to focus research attention on the general rules for constructing special-purpose languages. The case of remote manipulation is a good example of a bounded communications area, one which is important in its own right to Navy operational goals. It is planned that language elements will be implemented at the man-computer interface. The relationship of variations in these elements to total system performance will provide the data upon which practical human factors design guidelines will be based.

The theoretical effort in this first year has involved analyzing the information requirements for the operator, computer and manipulator, and evaluating alternative man-machine communication techniques and feedback mechanisms to derive effective communication procedures. Simultaneously with the theoretical evaluation of communication techniques, an experimental evaluation of two distinct computer-aided manipulation techniques was performed. The experiments involved a prototypical multi-moded supervisory controller, a wide variety of manipulation tasks, and a high-performance manipulator arm. Emphasis was placed on man-machine system performance. The experiments were designed to demonstrate the performance effects that can be expected when an operator uses a number of computer-assistance functions to perform tasks differing in complexity and control requirements. A sufficiently large number of subjects were tested over a long enough time to obtain reliable performance data. The data base not only contributes to the present findings but also forms a baseline for further evaluations of more advanced supervisory command languages.

2. REMOTE MANIPULATOR COMMAND LANGUAGE ANALYSIS

2.1 Overview

In this chapter we conduct a more detailed analysis of the roles played by man and machine in remote manipulation, and identify the essential reasons for the apparent poor performance of current systems. This leads to a different task allocation for man and machine, necessitating a particular form of communication between them. To analyze the requirements of such a communication on a more solid basis, we present a procedural net model for hierarchical task description. Following the discussion of the net we present a discussion of the necessary capabilities and mechanisms of a man-machine command language. Prototypes of these capabilities will be developed and evaluated in the experimental part of next year's program.

2.2 Two Paradigms

Teleoperators are intended to perform general purpose tasks in environments with uncontrolled structure. Teleoperators not only perform a wide variety of tasks, but also perform irregular mixes of task types and tasks with very little repetitiveness where specially designed machinery cannot be justified. Similarly, the environments in which teleoperator tasks are executed are seldom known in advance, unlike environments for special-purpose machines, such as an automatic part inserter for which the part to be inserted arrive in a precisely defined groove and in a well-specified orientation and rate. Teleoperators are intended to be used particularly in those instances when it is inexpedient to spend the effort to control the environment to the degree necessary for special-purpose machinery. However, current teleoperator control systems can be cast into one of two general paradigms, both of which can be shown to contradict the goals of performing general tasks in uncontrolled environments.

2.2.1 Machine Shop Paradigm. This approach views the man-machine system as being similar to the control situation in a machine shop where a mechanic operates a precision lathe. The machined object is securely held in a gripper and rotated in a constant speed around a fixed, stable axis. The machining tool is also held in a gripper but it can be moved around deftly in the plane containing the axis of rotation by two precise control wheels perpendicular to each other. The mechanic, with the well-illuminated machined object in his plain view controls the two wheels with his hands, causing the machining tool to cut through the machined object in the precise trajectory needed to form the goal shape.

This control approach has been carried over to the teleoperator system almost intact. The object operated upon is securely held or affixed to the ground and the operator individually controls -- through potentiometers, joysticks, switches or master/slave arrangements -- each link of the teleoperator. Notice also that visual inspection is almost exclusively used as the feedback channel. In such direct control the human operator has to provide several smooth and coordinated analog signals to accomplish a task at which he is at best slow and inexact, getting worse as the number of signals needed increases or his visual field becomes obscured. With sufficient training a mechanic can control a lathe quite effectively, but in the control of a dexterous manipulator with five, six or even seven degrees of freedom the limits of human capabilities are approached, resulting in the more than 10 to 1 performance ratio when comparing a controlled manipulator with a free diver (Pesch, 1970). Thus, using the machine shop control approach reduces the effectiveness of the teleoperator in performing general purpose tasks. Even master/slave arrangements, which replace the conscious control of several links with the natural human capability to control his arm and hand, just postpones the moment of judgment slightly. The operator can control the master mechanism properly if it behaves normally, but if time delays are introduced,

inadequate tactile feedback or high inertial forces are present, then his performance again degrades very steeply (Hill and Sword, 1972).

2.2.2 Programming Paradigm. In this approach the manipulator control problem is taken to be analogous to the control of a digital computer. The computer can perform a finite set of primitive actions and it can also read and execute a coded form of these commands represented internally in a program. To cause the computer to perform a task, the human programmer expresses the task in full detail as a sequence of the primitive actions specifically stating the actions to be taken in all eventualities. He then feeds this "program" to the computer and turns it loose for execution. Because of the speed of the computer's execution the human is essentially taken out of the control loop during the actual execution of the task.

Several variations and refinements of this approach have been adapted to teleoperator control, mainly by the Artificial Intelligence community (Minskey, et al, at MIT, McCarthy and Nillson at Stanford, and others). Here the elemental motions of the manipulator are the primitives and a detailed sequence of actions is developed ahead of time to accomplish the intended task. This approach is successful only in a very rigidly controlled environment, such as a completely automated segment of an assembly line. In other, less controlled environments, and more in general purpose tasks, such as those of the STRIPS system, success was very rudimentary (Fikes and Nilsson, 1971). The problem lies in the fact that while a computer program is executed in a well defined digital environment, where every command has an explicit outcome which is known in advance in full detail with all its side effects, it is not so with manipulator actions. Here the details of the environment are not known in advance, particularly, the exact relations between the manipulator and the various objects with which it interacts. This is an inherent inaccuracy and not one which will be alleviated by more advanced technology.

Moreover, nobody has devised a language powerful enough in its expressive and inference capability to describe an event in the real environment, much less, to express a dexterous action with all its possible consequences. The lack of such language prohibits planning complete tasks ahead of time -- i.e., the programming approach. In the STRIPS system a formalized model world is used for which the expressive power of assertions in first order predicate calculus is sufficient, and even then only very simple tasks are solvable.

To summarize the discussion of these two prevalent approaches, their failure can be attributed to faulty task allocation. Fast and exact control of a dexterous manipulator often exceeds human capabilities, and complete planning of a detailed task is beyond current computer capabilities. As long as we cannot have an autonomous manipulator with independent computer control we must use an effective man-machine symbiosis.

2.3 The Use of Sensory Information for Control

A new approach for manipulator control was presented recently (Finkel, Taylor, Bolles, Paul, and Feldman, 1974) which bypasses the need for machine shop accuracy in manipulator control. The idea is to control manipulator motion by conditional tests on sensory information. Hence, the command is no longer:

"Move to coordinates (X_1 X_2 ... X_7) in link Space"

but rather it is of the type:

"Move down until you touch a surface"

The move terminates when a prespecified sensory event occurs. If we reflect upon our own way of controlling simple manipulative arm motions we find striking similarities. To pick up a pen from the desk we first locate the pen visually, then we stretch our arm in that general direction correcting the motion according to the visual sensory information. The final approach and grasp are done using touch information for the alignment and application of grasping force. There is no complete preplanning with blind execution. This can be immediately shown by trying the same simple task with closed eyes after the initial location of the pen. Much more touch search takes place to compensate for the lack of visual correcting information. When the touch information is eliminated, the task is performed only if the initial aim is correct. There is no room for errors and no mechanisms to overcome the inherent inaccuracies.

2.4 Man-Machine Task Allocation

To effect a proper task allocation for man and machine in the teleoperator system function we have to face the fact that there is a large gap between the terms naturally used by the human operator to describe a task or an event and those "used" by the manipulator. The man describes a task in a high level, symbolic, goal-oriented language such as:

"Retrieve three sand samples"

where "retrieve" and "samples" refer more to the intent and purpose of the action and objects than to the motor motion or geometric description. The teleoperator hardware, on the other hand, can handle only low level, specific commands (e.g., to fix a specific link position or to sense the activation of a given touch sensor). This gap can be closed either

by the man going down to the low level of motor control, or by a computer raising the level of the machine to the human task-oriented level. Both of these choices were shown to result in poor performance. The third possibility is to meet somewhere in the middle with a computer raising the apparent behavior of the machine to a level which is more natural to the user than is direct control. This approach is termed supervisory control or computer aided control (Ferrell and Sheridan, 1967).

In supervisory control the human operator performs the high level planning of the task; he then communicates his plan in some form to the computer. The computer develops each step in the plan to a detailed sequence of commands appropriate for the manipulator, utilizing sensory information as feasible to guide the actions through the physical environment present at the time of execution. In such a supervisory mode of operation, there is no need to communicate back to the operator all the raw sensory data such as force or touch information utilized by the computer. The communciation in this direction can also be more task oriented. The computer need only inform the operator what task is being performed, and its progress. Now, what language is best for these dual requirements of command and feedback?

There have been a number of efforts, especially in the area of information retrieval, to use a restricted subset of plain English as the man-machine communication language, arguing that this is the most natural language for the operator and would lead to the best performance. We concur, however, with Ferrell (1973), who conducted simple experiments showing that a structured but flexible artificial command language can enable the operator to do his work more efficiently as well as simplify the process of machine translation. The advantage comes from the fact that, although entire manipulation tasks and goals are readily and perhaps most easily described by a person using ordinary English, the

complex geometric, spatial and temporal configurations of objects that need to be transmitted even in a high level manipulator command are not readily formulated in English. Verbal thinking is not well adapted to such description, people seldom have to do it, and when there is a need, graphic or other aids are usually employed. Furthermore, the flexibility of the English language, providing several ways to express the same idea, actually degrades operator performance relative to a well-structured language with primitives oriented to the specific task at hand. With such flexibility the operator has to make a choice before every command he gives.

2.5 The Procedural Net Model

To be more concrete about language structure and requirements, we have to formulate them within a general model of manipulator tasks. A clear understanding of the hierarchical relations among different tasks in a given problem domain can also help in the development of a more autonomous manipulator system. At the beginning only simple tasks will be autonomously controlled by the computer and as we learn more about these relations more complicated subtasks can be relegated to the computer and the operator can treat them as primitives in his communication language.

A hierarchical model based on the concepts of procedural nets (Sacherdoti, 1973 and 1975) was developed at Perceptronics (Shaket and Leal, 1976) to represent the hierarchy of tasks a manipulator can perform and the planning process which bridges the gap between a task described at high level of abstraction and a specific detailed plan to be executed by the teleoperator. According to this model the communication between man and machine is a description of the plan of action at some intermediate level of abstraction where the human develops the plan from the top down to an intermediate level and then communicates the plan at that level to the machine. The machine (computer) develops it to the primitive

level of manipulator command, and then actual execution can commence. We describe in this section the hierarchical model, the requirements imposed on the communication language, and some human factors considerations regarding the physical communication interface.

The procedural net is a conceptual framework modeling the process of plan development. The problem domain is described as a hierarchy of tasks and subtasks at various levels of abstraction. Each task node is made of a goal statement -- what has to be accomplished by the task, an object on which the action is performed, and an action -- the sequence of subtasks expressed at a lower level of abstraction. The specific sequence needed to accomplish a task is a function of both the state of the environment and what is requested at higher levels of the global task.

When a task is given at a high level a hierarchical structure like the one shown in Figure 2-1 can be generated expressing the plan in progressively more concrete and detailed terms. At the bottom level, the plan becomes a linked sequence of primitive actions which the manipulator can perform directly. In Figure 2-2 we describe part of the procedural net to accomplish the task: "shut valve". At the top level the task description is independent of valve type and valve location so it can be used in many ways as a step in more general plans. The parameter that is needed at this level is an indication of which valve is to be closed. One level lower in the task, "bring gripper to valve", the valve location is needed. At the level underneath it a specific manipulator configuration has to be decided upon. At the most primitive level, individual motor actions have to be specified. As the plan is developed from the top down more concrete facts about the environment and the configuration of the manipulator in relation to it have to be incorporated into the developed plan.

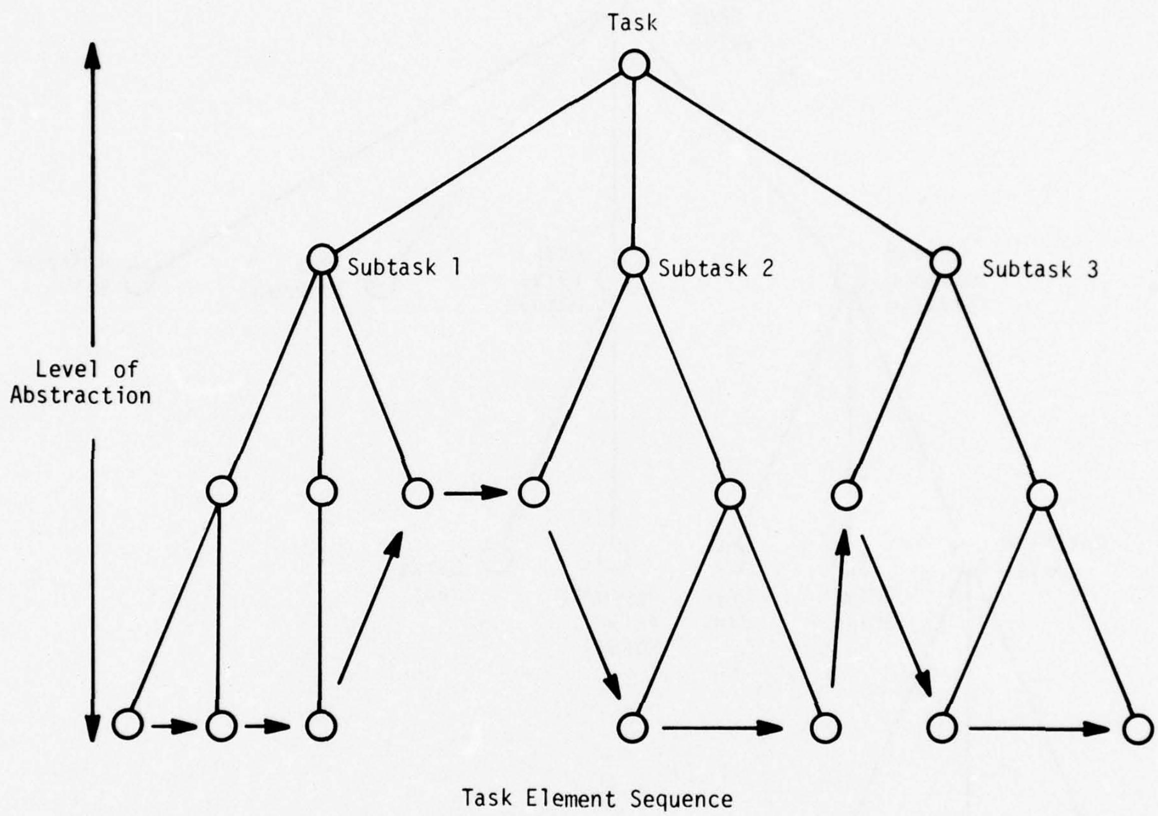

FIGURE 2-1. PROCEDURAL NET FOR REMOTE MANIPULATION

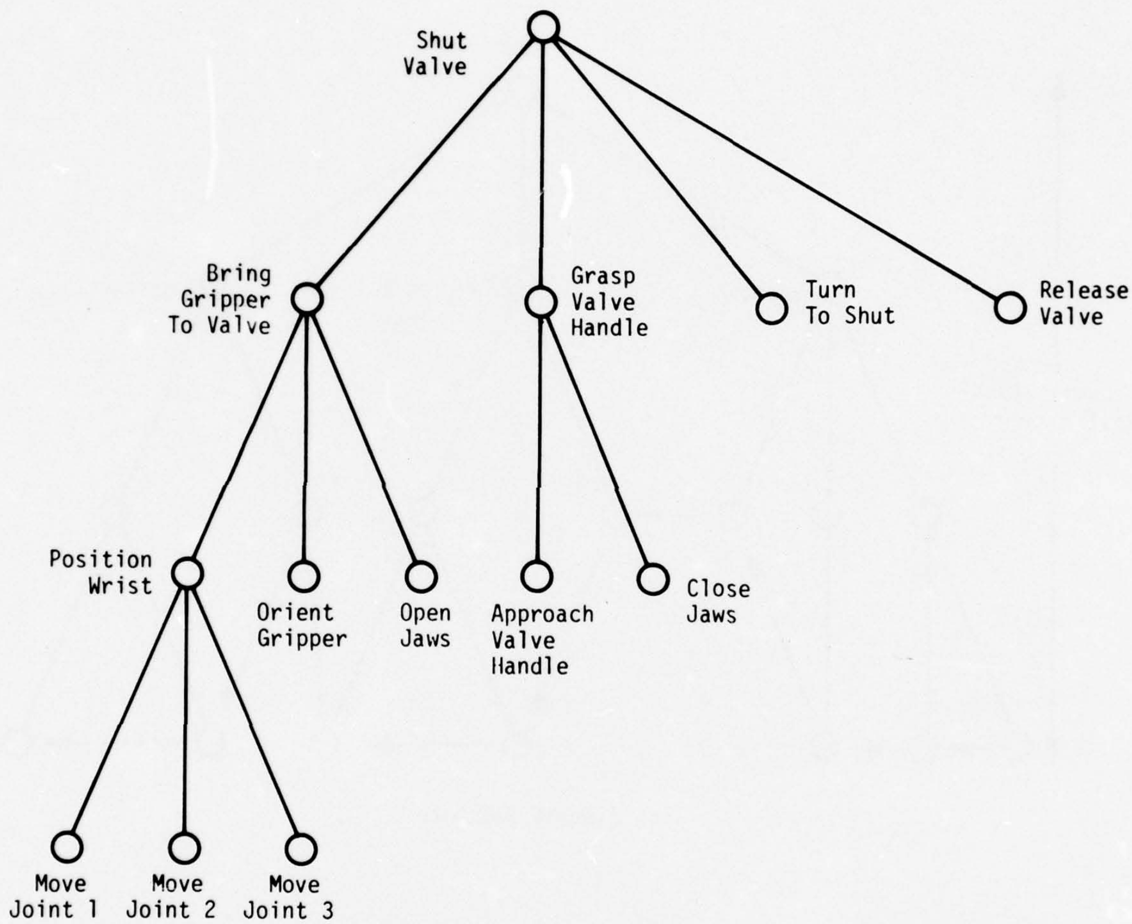

FIGURE 2-2. PARTIAL PROCEDURAL NET FOR "SHUT VALVE" TASK

Figure 2-3 represents the role of communication between man and machine as represented by the procedural net model. The operator conceives the task at a high level of abstraction and develops it to some intermediate level. Here the task is represented as a chain of subtasks. The operator has to communicate each of these subtasks in turn, indicating what has to be done, how it is to be done, and on which object in the environment. He has also to communicate the sequencing relations between the subtasks. These subtasks are now represented internally in the computer, shown as the nodes at the top level of the computer's net, and then developed down to primitive manipulator commands. Each node is actually a task complete with termination conditions, possible error reports, and links to the tasks to be performed before and after it. In Figure 2-3 these links appear as the arrows connecting the tips of the procedural net.

2.6 Effect of Basic Aiding Functions

This year's experiments were designed to examine the effects on man-machine performance of raising slightly the level of communication. Resolved Motion Control (RMC) and Automatic Motion Control (AMC) are examples of such higher level primitives. In resolved motion control, movement of a joystick causes the manipulator to move in the operator's geometric space rather than in the manipulator's link space. Our experiments have shown that this is a more natural arrangement for the operator, reducing both training time and improving performance level.

AMC is a command to move to a prespecified point in space. This is a complete motion sequence and the operator is freed from the concern of which link motions are needed to accomplish a task. The command is symbolic with no analog signal necessary. Again, our experiments have shown that with proper design of the command it can improve performance in the appropriate tasks. Even for such a simple command as AMC,

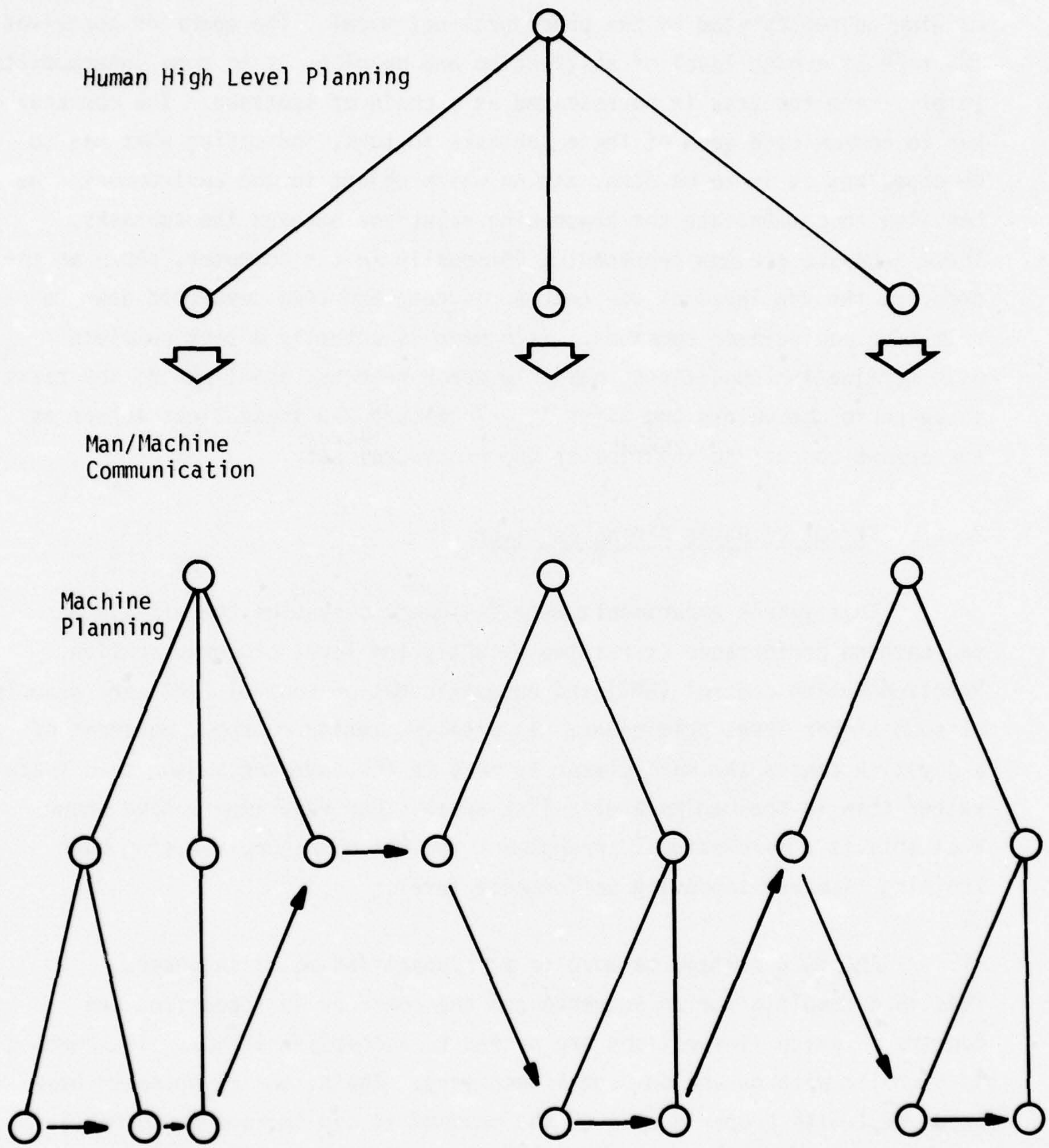

FIGURE 2-3. PROCEDURAL NET MODEL OF MAN/MACHINE COMMUNICATION

however, we can observe that a language containing symbolic references must have definition and executive modes. During the definition mode no task actions take place; the manipulator is brought to the different key points in the work space, and these are labeled and stored. In the execution mode these predefined points are called and the manipulator moves to the corresponding point.

When giving instructions in natural language we don't usually go through a definition phase. This can be attributed to the superior cognitive powers of man and the use of nouns as a referring mechanism. Instead of going to the chair in the corner and pointing to it saying "Let us call this chair #15" and then saying "bring over chair #15", we simply say "bring over the chair in the corner". The listener looks around, identifies an object to which the noun label "the chair in the corner" refers, and performs the required action. In a manipulator setting the most commonly available way to refer to a point is to physically move the manipulator to that point and record its configuration at that time.

From our experience with these symbolic commands we can derive some general recommendations for the design of symbolic man-machine communication language:

(1) Design an efficient definition mode -- to make shorter tasks benefit from the use of the computer aid.
(2) Design easy mechanisms to switch between modes.
(3) Execution commands must be short.
(4) A display of the state of the computer aid is needed in addition to a display of the environment.

2.7 Chaining Primitives

In addition to devising a framework for organizing more complex primitives the communication model points to the essential role of sequences of subtasks. In Figure 2-3 you can see that in general the top level task given to the human operator is expressed -- at the level of man-machine interface -- as a sequence of subtasks to be performed one after the other. Certain subtasks are regularly performed one after the other, and the capability to define them as a chain and call them as one unit can substantially reduce on-line communication requirements and hence improve performance. Also, by treating a chain as one unit the operator is given a higher level unit to handle, thus reducing his cognitive load. Adding the capability for chaining primitive commands is an essential part of next year's research program. The operator will be able to record any arbitrary sequence of manipulator primitive actions (or recursively other chains), name it, and then activate the sequence repeatedly by giving a single command. Effectively, the operator is taken out of the control loop during the chain execution, eliminating unnecessary delay.

2.8 Classes of Commands

Analysis of the model indicates that there are several basic classes of commands necessary for effective man-machine communication. These are needed in addition to the definition and execution commands described previously in this chapter. Actual experience with such a language will provide knowledge about which specific commands in each class are useful and what form they should take. The general classes are:

(1) Execution commands -- to call the actions from which more complex sequences will be constructed.

(2) Definition commands -- to label new points and define chains and parameters.

(3) Editing commands -- to link or modify existing chains.

(4) Mode controlling commands -- to cause changes in control mode, e.g., from automatic execution of a chain to manually controlled motion.

(5) Metalanguage commands -- to enable changes to the language itself which will make commonly used commands shorter.

Elements from all these levels must be combined into a concise, clean language. The basic purpose of the computer is to aid the operator in controlling the manipulator, so using the aid itself should not add more complexity than it overcomes. Hill and Sword (1972) describe an automatic control system for a simple manipulator which has both symbolic and analog primitive commands. It demonstrates elaborate mechanisms for mode changes between four different levels of increasingly automatic supervisory control. Some of the supervisory controlled primitives use information from touch sensors mounted on the end effector to cause action termination. Hill and Sword's system does not have the chaining capability, however, and its mode changing hierarchy tended to be complex for the user. Next year's research is aimed at demonstrating and evaluating a simple structured language containing all the elements given above. The object is to get experience and insights into the relations between the set of primitives, language mechanisms, the man-machine interface, and system performance.

3. COMPUTER-AIDED MANIPULATION FACILITY

3.1 Overview

Perceptronics' computer-aided manipulator facility, shown in Figure 3-1, includes a hydraulic servo manipulator, a 3-dimensional display, a man-machine interface, and a minicomputer. The functional relationships among the hardware components of the manipulator and display system are shown schematically in Figure 3-2. An operator controls the manipulator through the joysticks and pushbuttons of the control console; he observes the manipulator activities through direct viewing or via the 3-dimensional display. The operator's inputs are processed by the minicomputer; the minicomputer in turn controls the manipulator servo electronics and responds to the manipulator's position-sensing potentiometers. Data communications between the minicomputer and the control console or manipulator electronics occur via the programmable interface. The individual components of the manipulator and display system are described in the following paragraphs.

3.2 Servoarm Manipulator

3.2.1 Mechanical Configuration. The Servoarm manipulator, shown in Figure 3-3, is electronically-controlled and hydraulically-powered. As illustrated in Figure 3-4, the manipulator has six rotating joints (each with a full 180° movement range) plus gripper closure. The arm motions and joint numbers are (in anthropomorphic notation):

(1) Shoulder rotation
(2) Shoulder elevation
(3) Elbow flexion

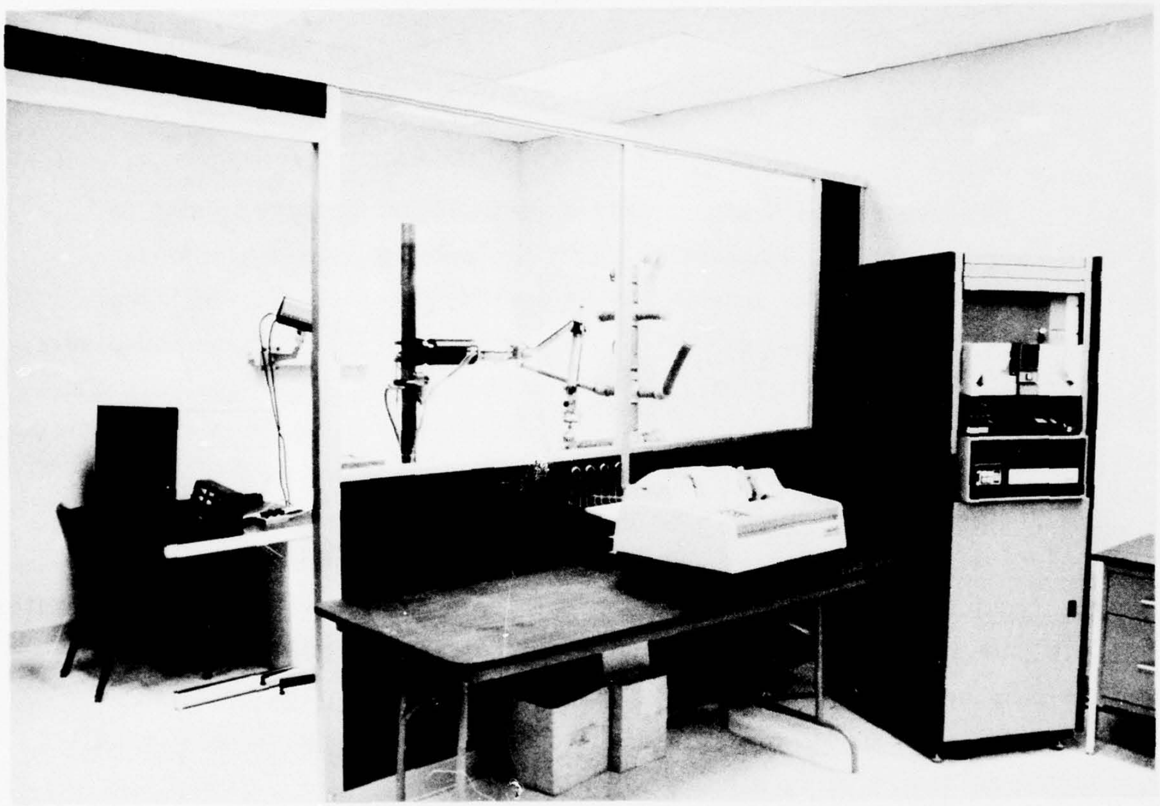

FIGURE 3-1. PERCEPTRONICS FACILITY FOR COMPUTER-AIDED MANIPULATION

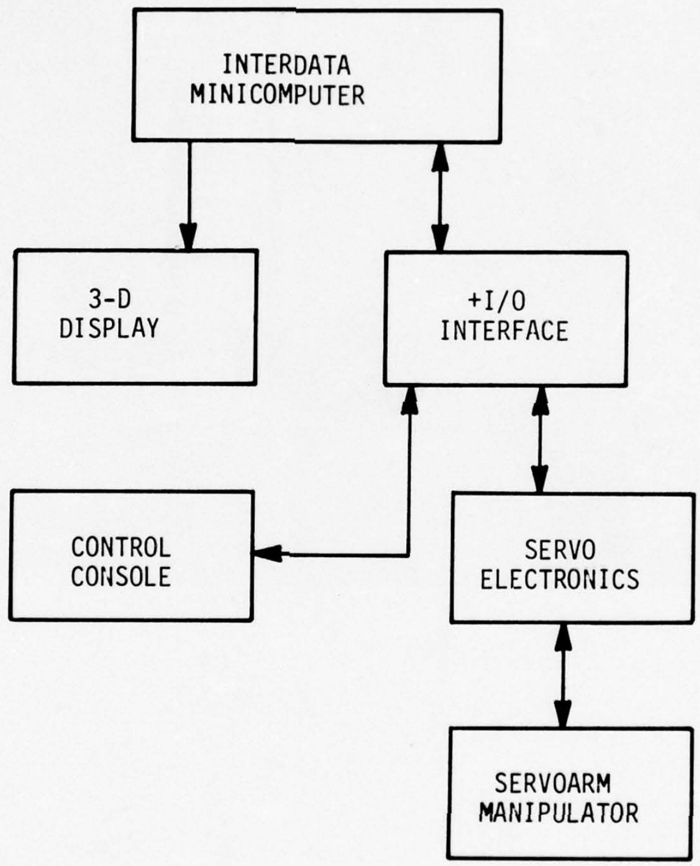

FIGURE 3-2. MANIPULATOR AND DISPLAY SYSTEM

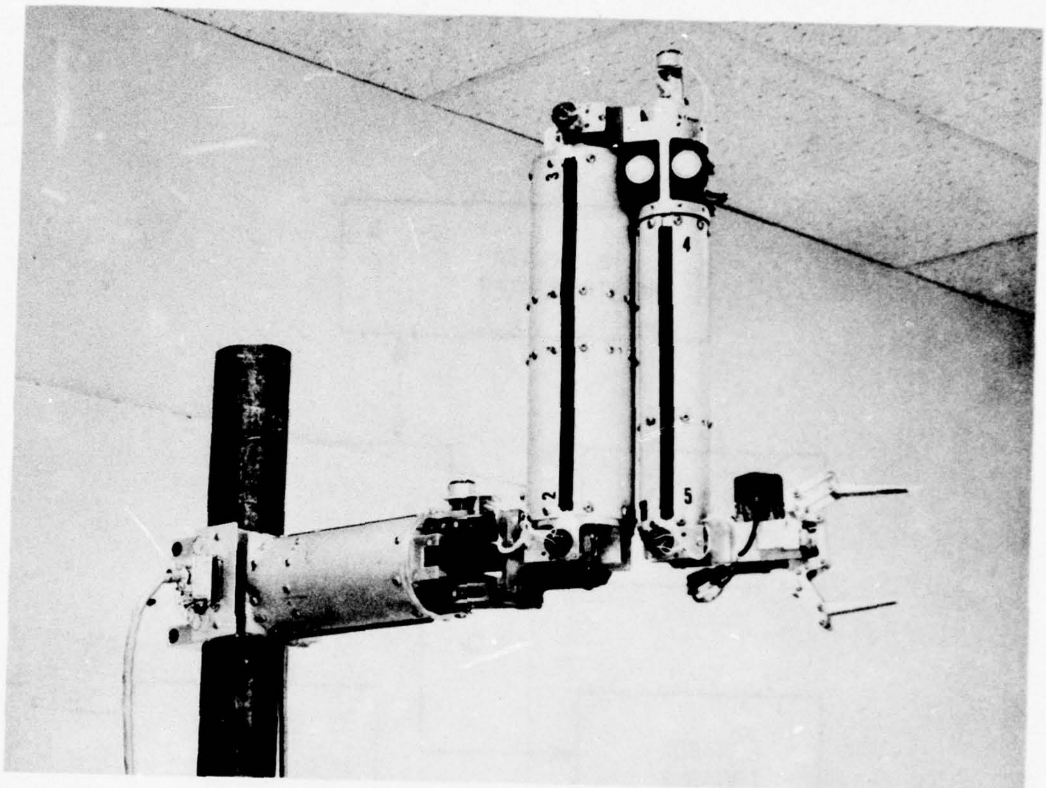

FIGURE 3-3. SERVOARM MANIPULATOR

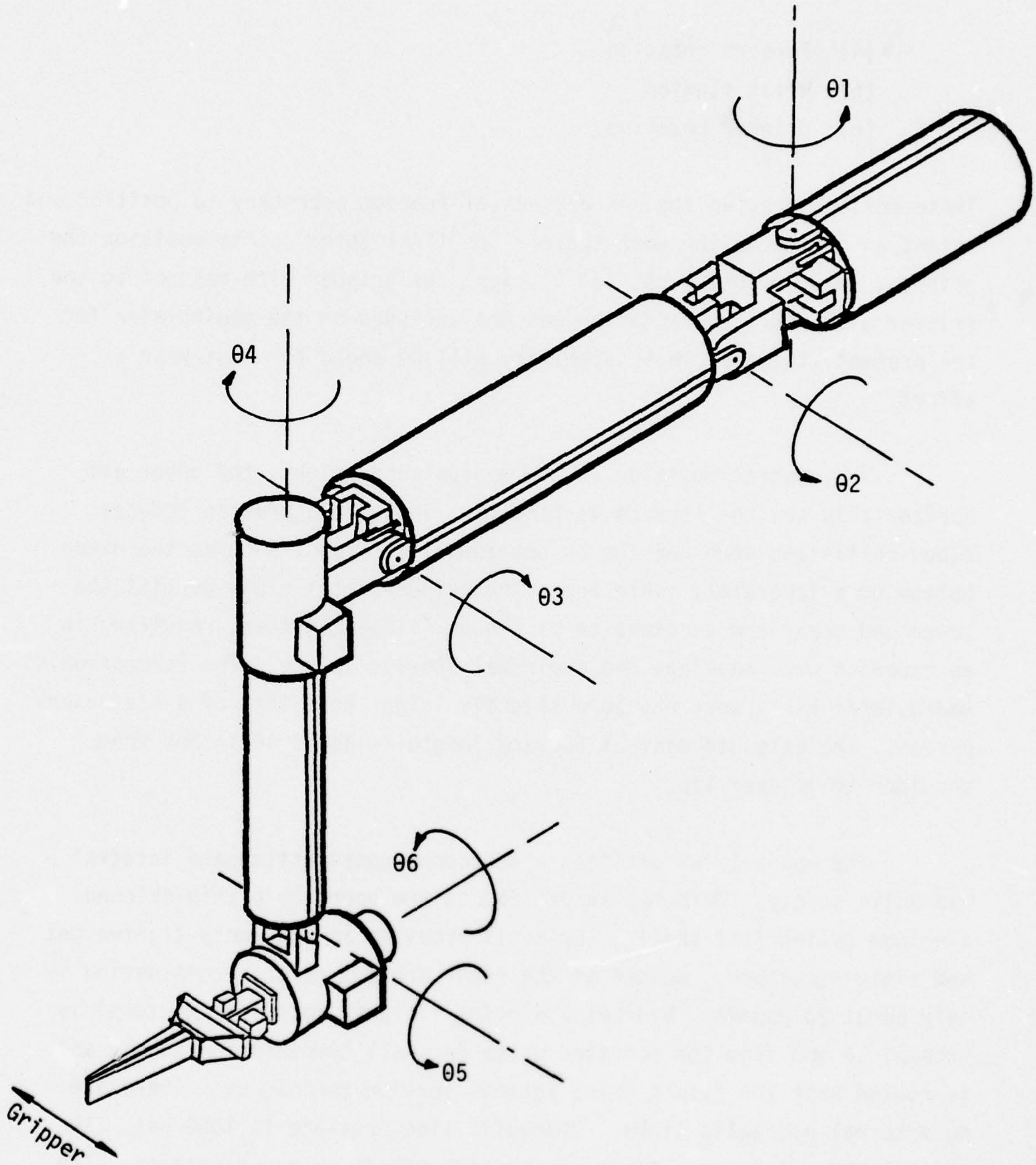

FIGURE 3-4. SERVO MANIPULATOR WITH MOTIONS OF THE SIX ROTARY JOINTS

(4) Forearm rotation

(5) Wrist flexion

(6) Gripper rotation

These motions provide the six degrees of freedom necessary to position and orient an object in the work space. The first three joints position the gripper, while Joints 4, 5, and 6 orient the gripper with respect to the gripper axes. Gripper rotation was not included on the manipulator for the present studies. This capability will be added for next year's effort.

The neutral position of the manipulator orients the upper arm horizontally and the forearm vertically. This configuration reduces elbow collisions when working on horizontal surfaces, such as the ocean bottom or a laboratory table top. The unique offset elbow permits the lower and upper arm sections to be brought close together, resulting in an expanded work envelope and a minimal stowage volume. The Perceptronics manipulator has a work envelope slightly larger than that of a stationary person. The extended manipulator arm length is about 40 inches from shoulder to gripper tip.

The manipulator utilizes a monocoque construction and integral hydraulic supply. Main mechanical forces are borne by a thin-skinned aluminum cylindrical shell. The shell provides an extremely lightweight and rigid structure. Weight of the total arm and gripper combination is only about 20 pounds. Hydraulic working fluid (a water-oil mixture) is brought to and from the actuator units in small transmission tubes, and is routed past the joints using various sealing techniques. There are no external hydraulic lines. Hydraulic line pressure is 1000 psi. The manipulator can exert a force of about 20 pounds in any direction. The combination of lightweight construction and hydraulic actuation makes the

arm fast as well as strong. For example, the extended arm can move smoothly at velocities well over 90°/second.

The gripper is illustrated in Figure 3-5. It is a parallel jaw unit, and carries its own hydraulic servo valve. Grip strength is about 32 lbs at 1000 psi. The gripper is designed for quick disconnect of the jaws from the hydraulic assembly. This feature will eventually permit automatic tool change during underwater operation.

3.2.2 Actuator and Servo Control System. Figure 3-6 shows the actuator which rotates the forearm. It is typical of all other actuators in the arm. Each actuator has a pair of pistons and cylinders controlled by a single servo valve. The cylinders of the actuator are inverted, in that the piston is the static element and the cylinder moves. Cylinder movement is transmitted directly to the moving arm member by a pinned chain. Because the hydraulic actuators are low speed, high torque devices, as compared with electric motor actuators, no gears are required in the actuator. Elimination of gears reduces the weight of the arm.

Each actuator is controlled by a Moog rate-proportional servo valve which regulates hydraulic fluid flow to the actuator. The servo valve is, in turn, controlled by an electronic position feedback servo amplifier. This amplifier generates a control voltage to the valve according to the difference between an input command voltage and the output voltage of the position-sensing potentiometers attached to the actuator. Thus, the motions of the servo manipulator are controlled by an input D.C. voltage to each actuator servo amplifier. The command voltages to the servo amplifiers are output from the computer via digital-to-analog converters.

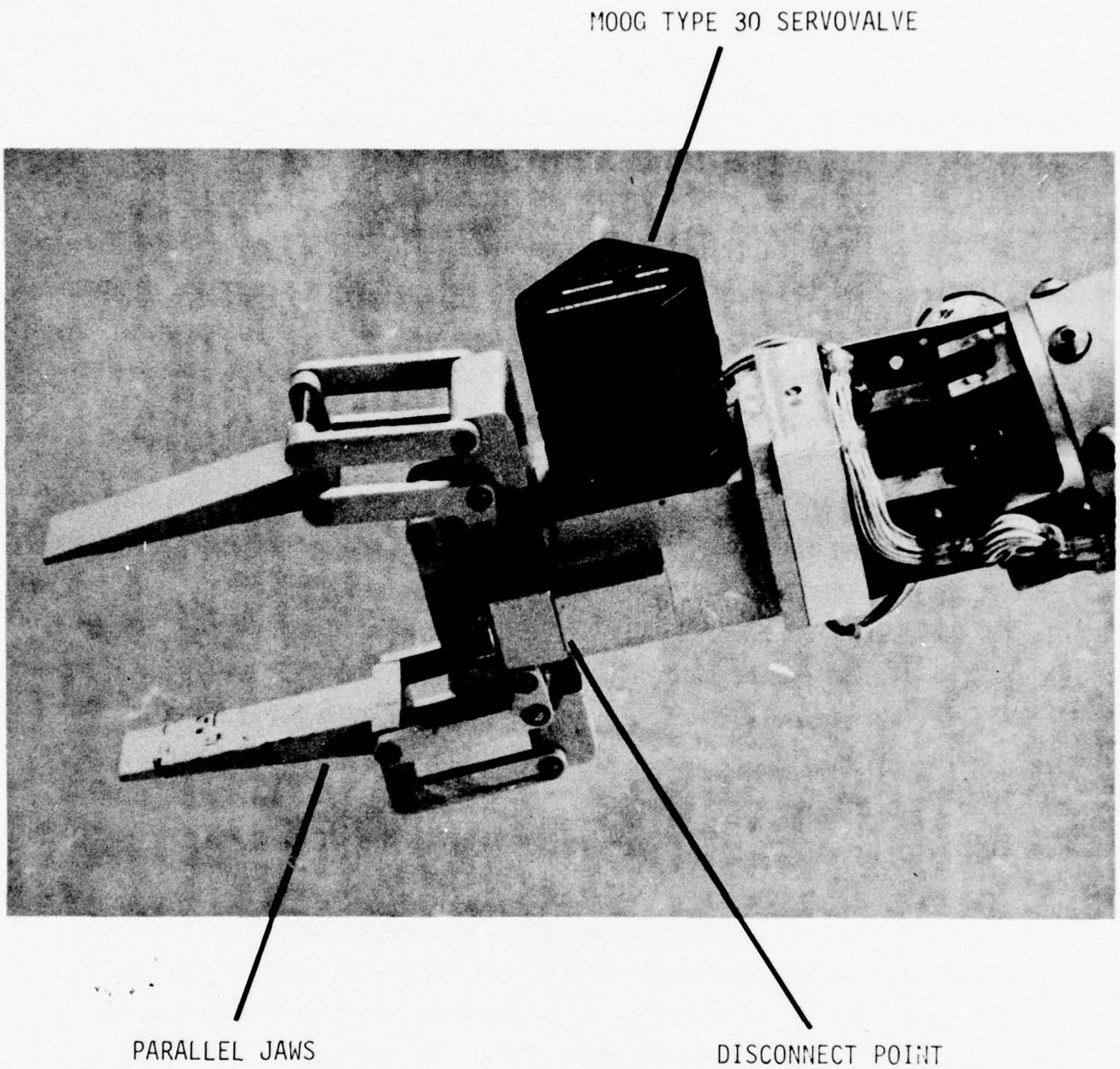

FIGURE 3-5. HYDRAULIC GRIPPER UNIT

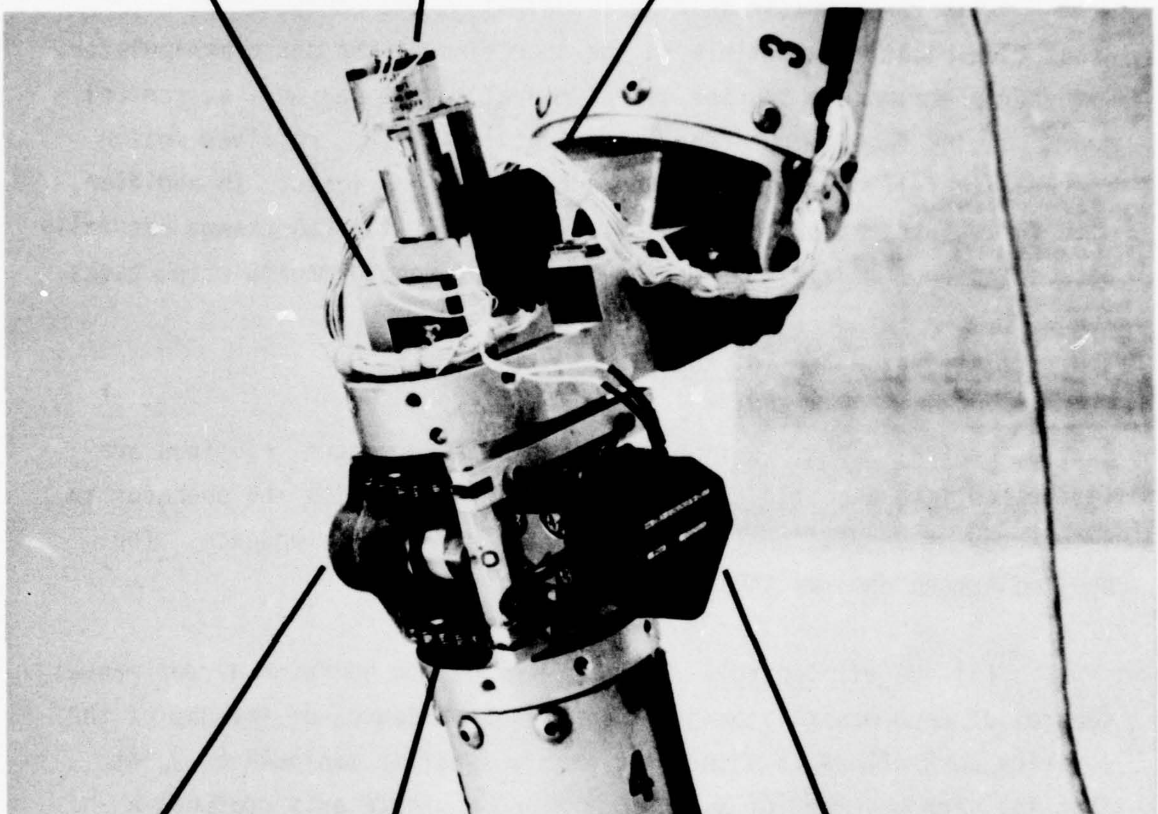

FIGURE 3-6. FOREARM ACTUATOR UNIT

With the computer in direct control of the manipulator, great flexibility is possible in the operation of the servo manipulator. Computer programs can provide direct manual control as well as control modes ranging from computer-assisted functions (e.g., resolved motion control) to fully automated performance of routine tasks. In addition, with fully integrated computer software, an operator can change naturally between control modes to perform a variety of remote manipulation tasks.

3.3 Integrated Control Console

3.3.1 Control Modes. A library of manipulator control routines are integrated into a single computer program which permits the operator to select any of several control routines in any desired sequence. The available mode options include:

(1) Direct Control. This mode gives the operator direct manual control of each manipulator joint angle. Each degree-of-freedom of the joystick controllers is associated with a specific manipulator joint. That is, each movement of a joystick along a single axis produces a radial movement of the manipulator about the controlled manipulator joint. To produce end-effector movement along a straight line, coordinated control of two or more manipulator joints is required. Thus, the operator must activate two or more joystick axes simultaneously.

(2) Resolved Motion Control (RMC). This control mode allows the operator to move the wrist along task or world coordinates. Each degree of freedom of the joystick is associated with movement of the manipulator end-effector along a specific X, Y, or Z axis of the work space. Figure 3-7 shows the X, Y, and Z orientations associated with wrist swing, reach, and lift, respectively. Under RMC the computer assumes the responsibility for performing complex coordinate transformations. The

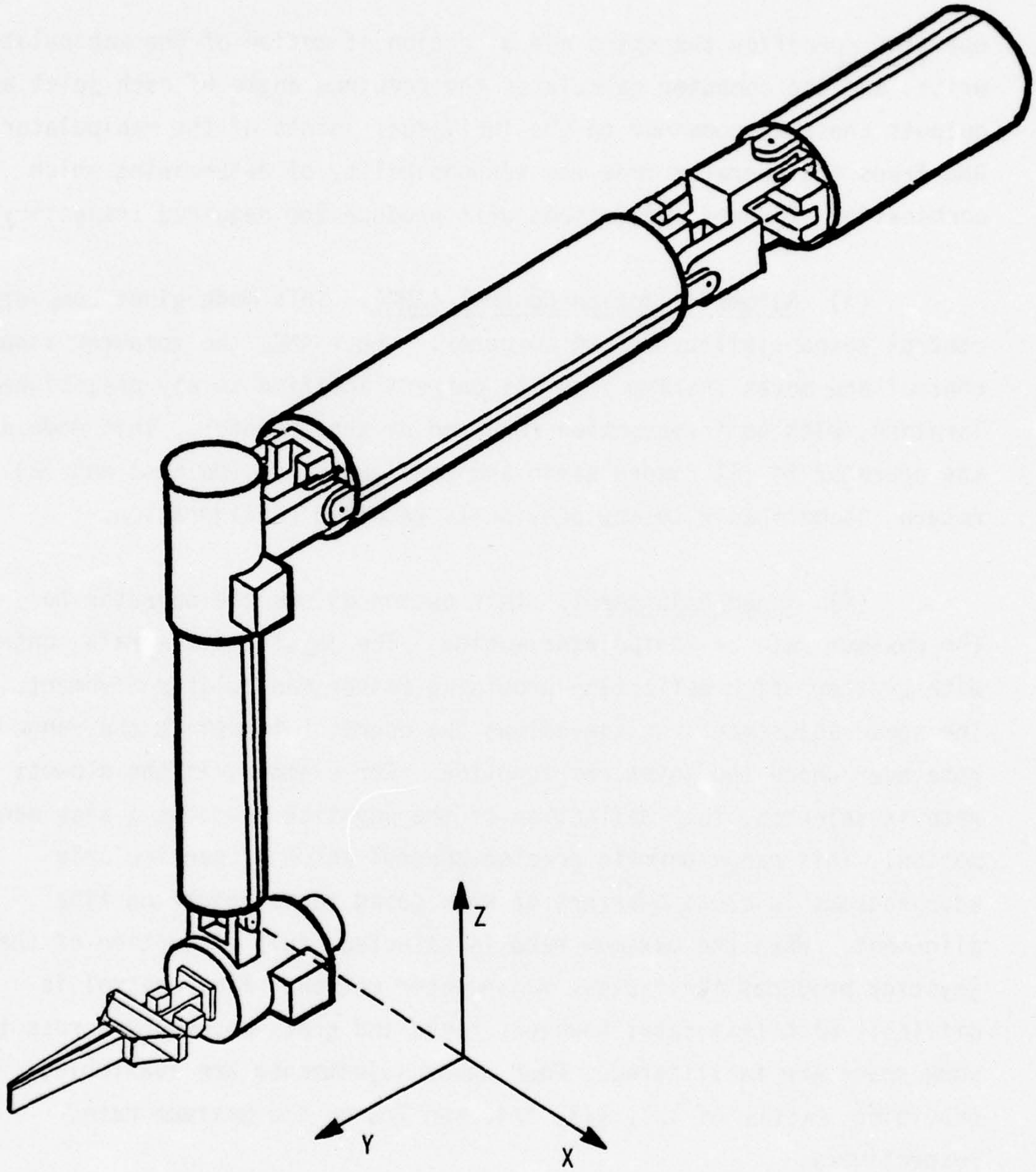

FIGURE 3-7. RESOLVED MOTION CONTROL
END-EFFECTOR COORDINATES

operator specifies the speed and direction of motion of the manipulator wrist, and the computer calculates the required angle of each joint and outputs these as commands to the individual joints of the manipulator. RMC frees the operator from the responsibility of determining which combination of speed and motions will produce the required trajectory.

(3) Automatic Motion Control (AMC). This mode gives complete control responsibility to the computer. Under AMC, the computer assumes control and moves the arm from its current location to any preassigned location, with no intervention required by the operator. This mode allows the operator to (1) record seven arm configurations (points) and (2) return automatically to any previously recorded configuration.

(4) Speed Adjustment. This option allows the operator to select the maximum rate of manipulator motion. The joysticks are rate controllers with greater stick deflection providing faster manipulator movement. The speed adjustment routine allows the operator to select the range of rate over which the joysticks function. For example, if the slowest rate is selected, full deflection of the joystick produces a slow manipulator motion. This range permits precise control which is particularly advantageous in close quarters or when doing tasks requiring fine alignment. When the maximum rate is selected, full deflection of the joystick produces the fastest manipulator motion. Fine control is difficult with this rate; however, rapid and gross movements across the work space are facilitated. Four speed adjustments are available, providing ratios of 1/1, 1/2, 1/4, and 1/8 of the maximum rate, respectively.

3.3.2 Console Configuration. The man-machine interface consists of a control console by which an operator can manually control arm motions, select computer assistance control functions, and observe control status.

The present control console, shown in Figure 3-8, includes a set of function pushbuttons (incorporating indicator lamps) and a pair of three-degree-of-freedom, spring-loaded joysticks. The pushbuttons, lamps, and joysticks are mounted together in a moveable, enclosure which can be placed on a table top. The enclosure provides a sloping surface on which the operator may steady his hands while manipulating the joysticks. Pushbuttons, lamps, and other manual controls are arranged on an easily visible slanted face, located behind the joysticks and within easy reach from them.

The operator uses both joysticks and the pushbuttons to control the manipulator. The joysticks are used for manual control and the pushbuttons are used for control mode selection. Using the pushbuttons and joysticks, the operator can smoothly take the manipulator through a sequence of tasks, selecting control modes, rates, and manual operations that are most appropriate for each subtask. For example, he may use AMC for gross movement from the stowed position to the target area. He can then change immediately to RMC for fine movements and for alignment and insertion. While in RMC mode, the operator can move the arm to the "drop" point, and then record the latter point to facilitate repetition of the task.

The operator uses the two rate-control joysticks to manually control the manipulator. The right joystick is used to position the end-effector in the work space and the left joystick is used to orient the end-effector relative to objects in the work space. The joysticks are used for both direct and resolved motion control. Control activations and manipulator joint movements for direct control and RMC are illustrated in Figure 3-9. The relationships between joystick motions and manipulator movements differ in direct control and RMC. In RMC, each axis of the right joystick controls joints 1, 2, and 3 simultaneously; whereas, in

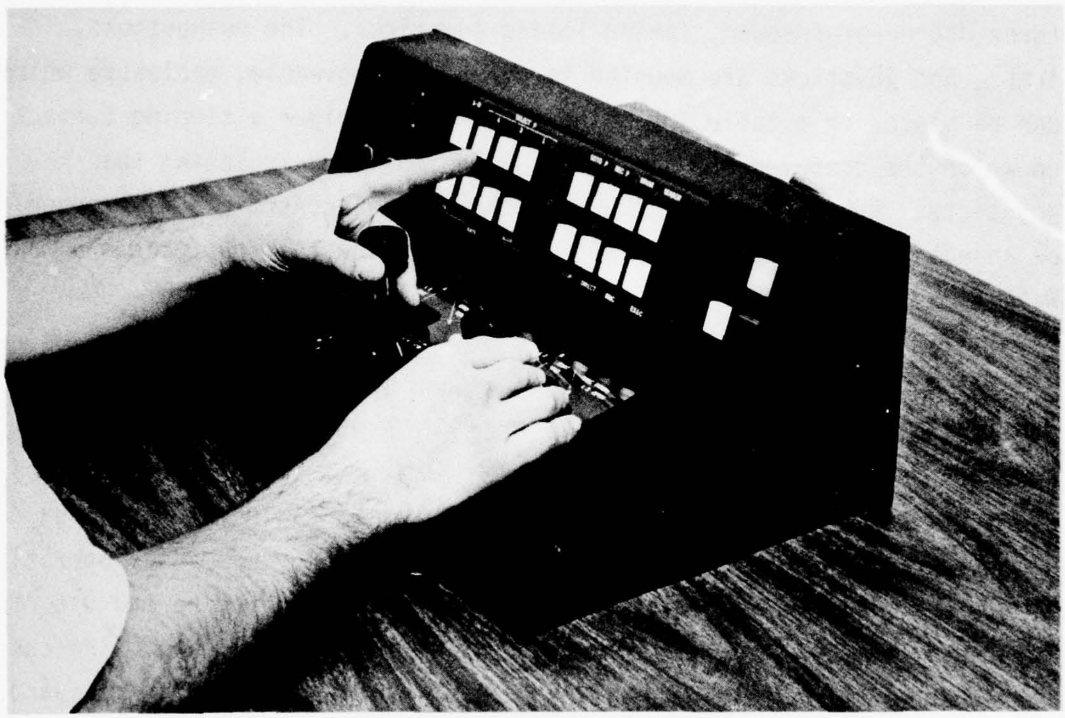

FIGURE 3-8. INTEGRATED CONTROL CONSOLE

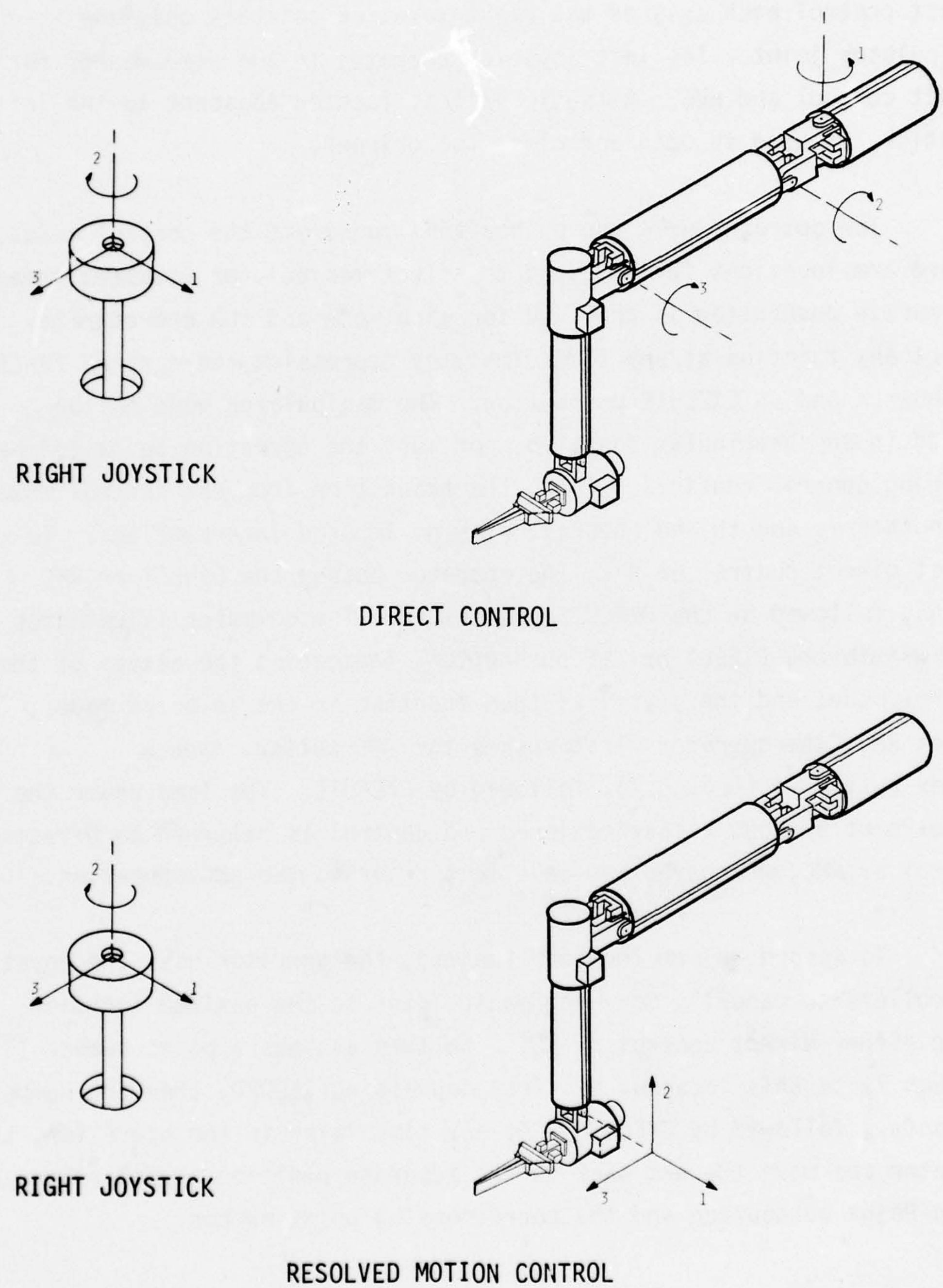

FIGURE 3-9. JOYSTICK MOVEMENTS AND CORRESPONDING MANIPULATOR MOVEMENTS

direct control each axis of the right joystick controls only one manipulator joint. The left joystick operates in the same manner for both direct control and RMC. A toggle switch, located adjacent to the left joystick, is used to open and close the gripper.

The operator uses the pushbuttons to select the control modes, to record arm locations for AMC, and to select manipulator movement speeds. A separate pushbutton is provided for each mode and the operator may select any function at any time simply by depressing the desired function pushbutton and an EXECUTE pushbutton. The manipulator need not be placed in any particular position, nor must the operation be halted before changing control routines. Thus, the transition from one control routine to another is smooth and natural, with no imposed interruptions. To select direct control or RMC, the operator pushes the DIRECT or RMC button, followed by the EXECUTE pushbutton. The computer illuminates the lamp within the DIRECT or RMC pushbutton, indicating the status of the control mode, and the joysticks then function in the selected mode. To select AMC, the operator first pushes the AMC button, then a number button (1 through 7), followed by EXECUTE. The lamp under the Go-To-Point buttons is extinguished and control is returned to direct control or RMC, whichever was in effect prior to the AMC operation.

To record an arm location (point), the operator uses the joystick controllers to manually move the manipulator to the desired location using either direct control or RMC. He then assigns a point number (1 through 7) to this location by first depressing RECORD, then the number button(s), followed by EXECUTE. At any time later in the operation, the operator can move the arm back to the recorded position by selecting the Go-To-Point pushbutton and the corresponding point number.

As presently configured, the pushbuttons used to designate arm configuration numbers are in binary notation. Thus, to specify the number 6_{10}, the operator must activate pushbuttons 4_2 and 2_2. Three number pushbuttons (4_2, 2_2, 1_2) are available, thus a maximum of 7 configurations can be designated.

3.4 3-Dimensional Display

Figure 3-10 is a photograph of the Perceptronics 3-D display. The system produces a real three-dimensional image, located a short distance behind the display screen. The image can be viewed without special glasses or optics, and can be photographed by single-lens or stereo cameras. Parallax is present, so that by changing viewing position, the user can look around the image for a better view of any side. Designed specifically for use as a computer output terminal, the display permits direct user interaction with the 3-D image.

The system has two major advantages over previous attempts at stereoscopic display. First, the three-dimensional image lets the viewer operate without visual restriction at a high level of stereo acuity -- in fact, several users can view the display at the same time. Second, the interactive capability lets the viewer operate on-line within the actual image space -- measure the distance between two points, for example, or to rotate the image for a better viewing angle.

The three-dimensional image is created by a patented mirror mechanism (Patent No. 3,371,155) positioned in front of a fast Cathode Ray Tube (CRT) as shown in Figure 3-11. The mirrors vibrate forward and back to produce a volumetric image in the viewing area. The viewer looks directly at the CRT screen. This means that the image can be as detailed and as bright as the CRT itself, although actual resolution is determined

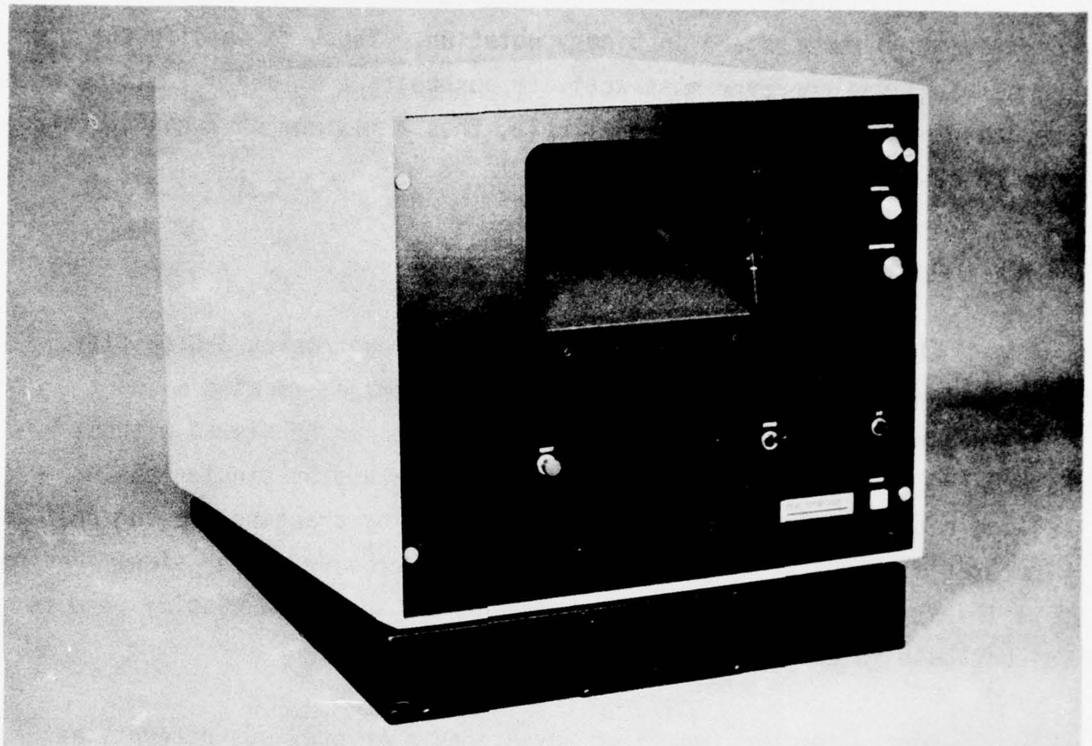

FIGURE 3-10. 3-D DISPLAY TERMINAL

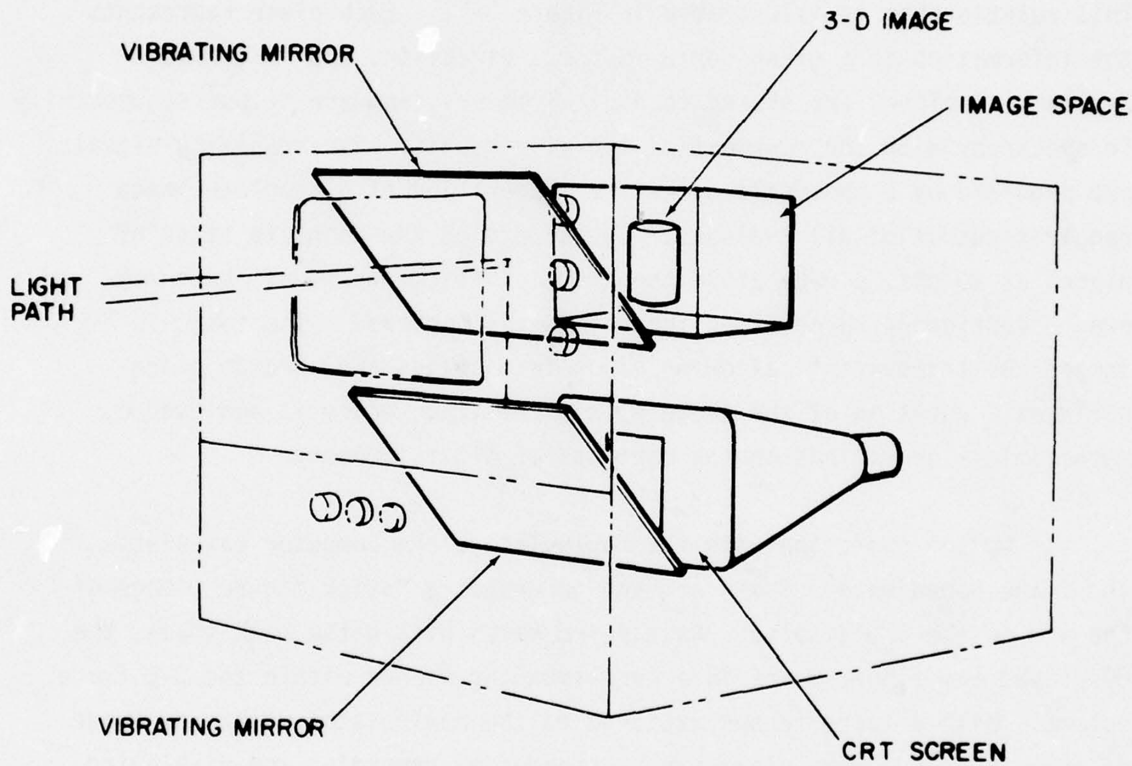

FIGURE 3-11. 3-D DISPLAY MECHANISM

by digital memory size and data throughput rates. The image space is about 5 inches deep.

In the computer, the image is made up of a stack of two-dimensional X-Y planes, where X and Y correspond to the dimensions of the CRT screen. This relationship is illustrated in Figure 3-12. Each plane represents the information at a given depth in the Z direction, and is termed a Z-plane. Z-planes are stored in digital memory, and are output sequentially in synchrony with the movement of the mirror unit. Synchronizing signals are provided by a photocell detector. Generation of a complete image requires output of all Z-planes. By outputting the complete stack of planes at 30 cps, a rate above the critical flicker rate of the human eye, a continuous three-dimensional image is achieved. The image is inherently transparent, allowing views into solids and through plane surfaces. Rotation of the image within the image space is achieved by mathematical operations on the contents of digital memory.

During operation with the manipulator, the computer calculates the image coordinates of the arm and generates a "stick figure" image of the arm on the 3-D display. As the arm moves within the work space, the displayed arm figure moves in a corresponding manner within the 3-D image volume. With a force sensor attached to the manipulator wrist, an image of objects in the work space can be created by recording and displaying those points in space where the end-effector touched the object.

Figure 3-13 is an artist's concept of three-dimensional display in use. Shown is the manipulator arm and a cylindrical work object. Once the outlines of the object have been established by contact mapping, the operator can position the manipulator in the image space to bring the end effector into contact with the work object, and can initiate automatic control routines, thus allowing task performance in visually degraded environments.

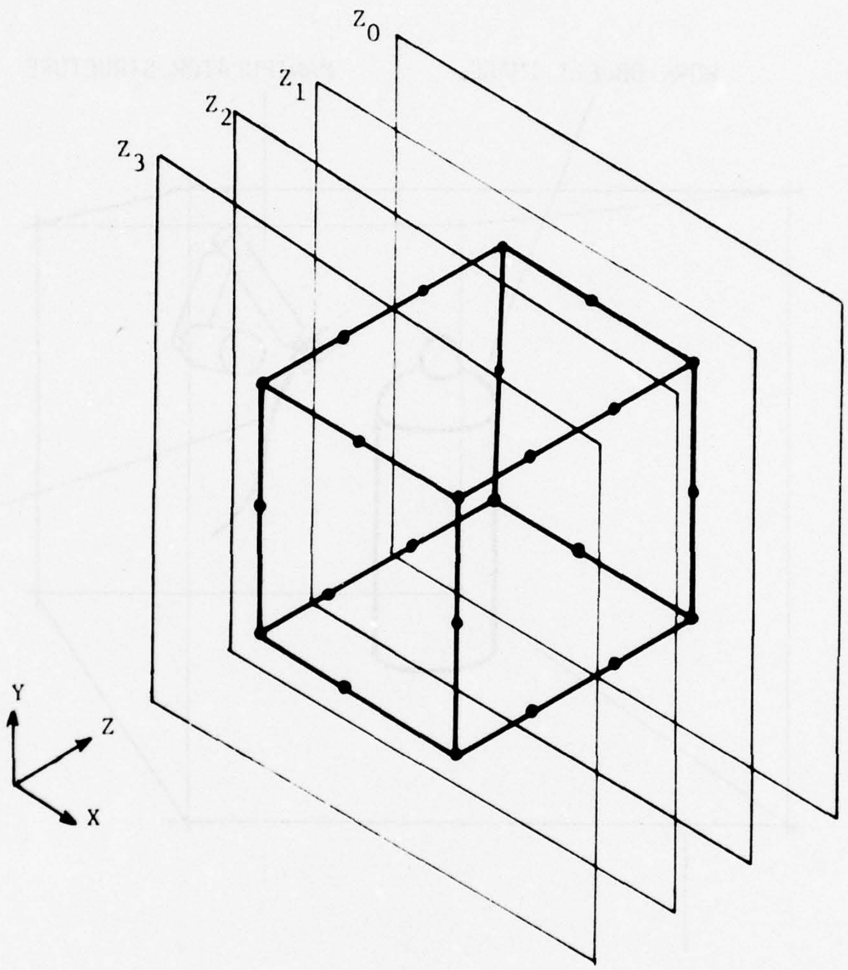

FIGURE 3-12. 3-D IMAGE GENERATION BY Z-PLANES

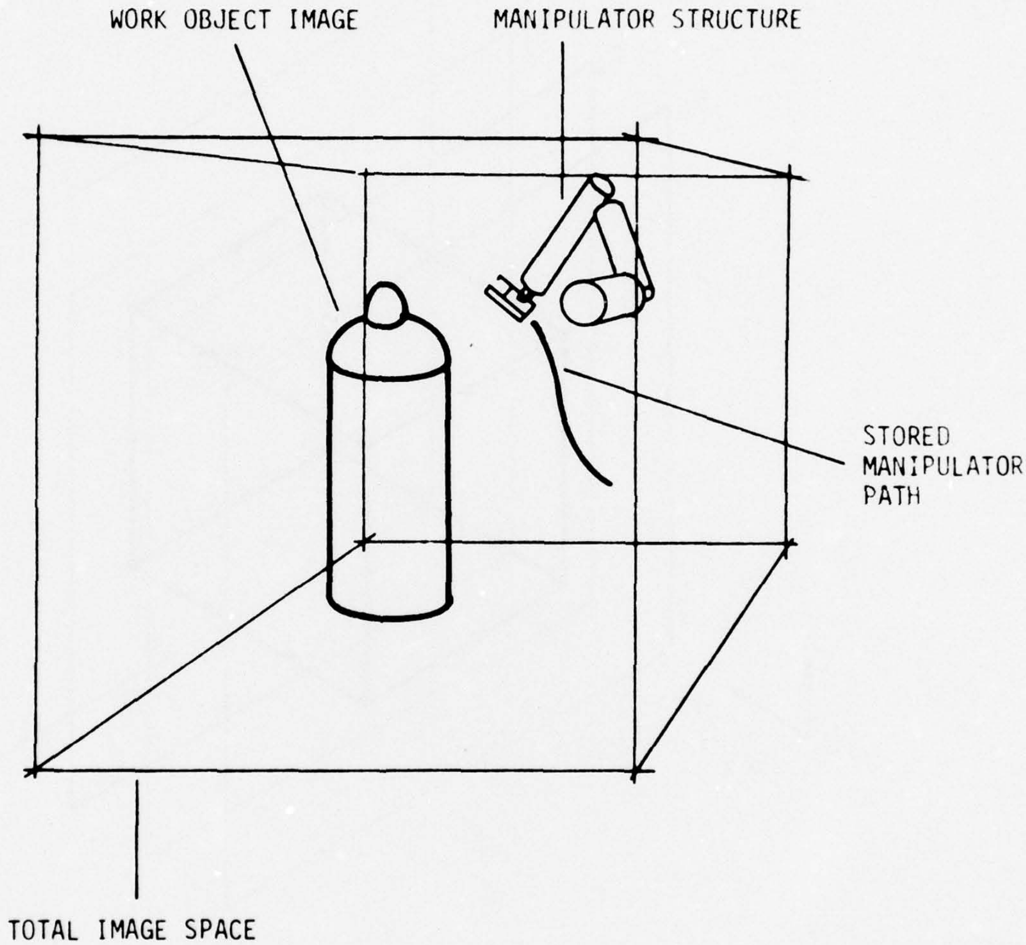

FIGURE 3-13. SAMPLE 3-D MANIPULATION DISPLAY

3.5 Computer Control System

3.5.1 Control Processor. The supporting processor for the manipulator system is an Interdata Model 70 minicomputer. This machine, which is microprogrammed to accept an imitation of the IBM system 360 assembly language set, has a memory cycle time of 1 μs and basic instruction execution times averaging between 1 and 3 μs. As presently configured, the processor system includes 48 kilo bytes of core memory, a high speed paper tape reader/punch, a line printer, a CRT alphanumeric terminal, a selector channel, a disk memory and a re-settable precision interval clock. The disk drive, CRT, and other preipherals are used to support program development work and are not part of the real time manipulator control system.

3.5.2 Processor Interface. Data transfer between the computer and manipulator servo-electronics and between the computer and the control console is performed by a Perceptronics +I/O Programmable Interface. Besides providing all analog-to-digital (A/D), digital-to-analog (D/A), and digital-to-digital (D/D) conversions among the system components, this interface allows the outputs of all controlled devices to be treated by the processor as if they were the product of only one device, thus simplifying the software arrangements at the processor.

The +I/O Interface contains a number of functional modules arranged along a transfer buss by which commands, data and status signals are communicated. These modules perform such individual functions as standardizing communication with the processor, sequencing data transfers across the buss, and performing D/A conversion and output.

In addition to an interface module between the processor and interface, the +I/O includes an A/D module that is used to interface

with the servo position potentiometers and control console joysticks. Thirty-two individually addressable input channels are provided. An eight-channel D/A module is used for converting and sending position commands (voltages) to the control inputs of the servos. Finally, a D/D module is used to provide the 16 input and output channels for the button and lamp arrays of the control console.

3.6 Computer Software System

3.6.1 Software Organization. Figure 3-14 illustrates the functional organization of the major software subsystems. The software was specifically designed so that interdependency of the functional subsystems is kept to a minimum. Accordingly, future changes and enhancements of each individual subsystem is more easily achieved. Also, modification of hardware elements do not seriously affect the existing software components. The major subsystems are:

(1) Physical Device Support Routines. These routines interact directly with the hardware, supporting such devices as the manipulator arm, operator's control console, and 3-D display.

(2) Virtual Device Routines. Virtual routines serve as the interface between the physical routines and the applications programs. Such routines allow applications programs to communicate with the physical devices in a manner most convenient to the given application.

(3) Three-Dimensional Routines. The 3-D programs serve as the interface between the 3-D display and applications programs.

(4) Spatial Transformation Routines. Transformations are used by many applications programs while controlling the arm, searching the work space, or mapping objects.

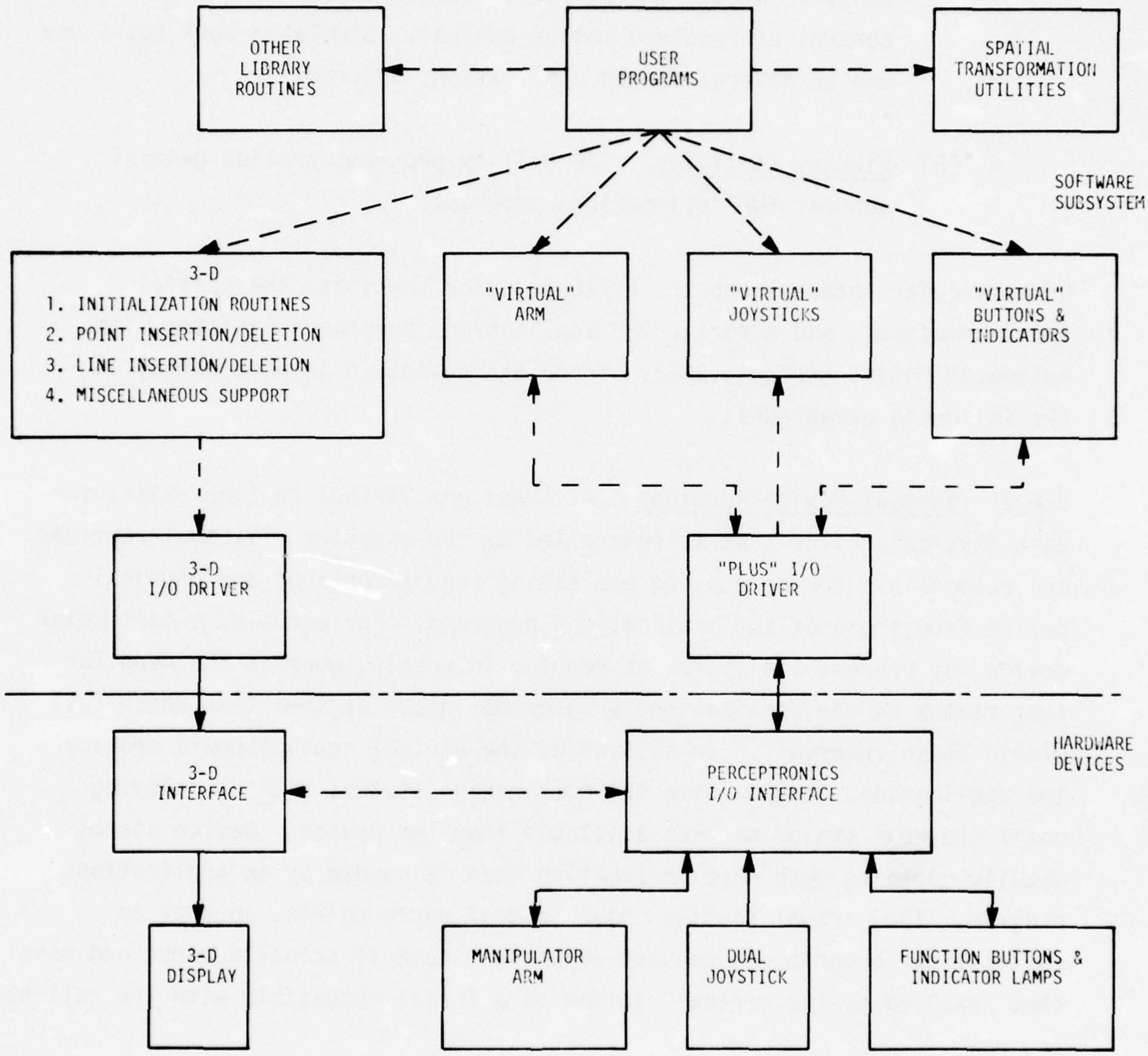

FIGURE 3-14. MANIPULATOR SYSTEM SOFTWARE ORGANIZATION

(5) Applications Programs These programs control all global behavior of the manipulator, such as motion under direct control or resolved motion control. Simulated work tasks use one or several linked applications programs

(6) Library Utilities. The utility programs provide general support for applications programs.

Of particular interest are the virtual device routines, the spatial transformations, and a particular applications program associated with Automatic Motion Control (AMC). These are described in more detail in the following paragraphs.

3.6.2 Virtual Device Routines. At least one virtual routine exists for each physical device that is controlled by the computer Virtual routines are responsible for decoupling the timing requirements of the physical device from those of the applications programs. For example, a particular device may present its status at regular intervals, whereas the need for that status by the applications program may occur at some time which falls within these intervals. In this case, the virtual routine would provide the applications program with the most recent status, without delaying until the next status becomes available from the device. Device status usually contains much more information than is needed by an applications program. The virtual routines have several entry points, so that an applications program can request only those data it actually needs and have them supplied by the virtual routine in a format compatible with the calling program.

Virtual routines also perform auxiliary functions that are needed by all applications programs. Localizing these functions to a single program module reduces the errors that result from modifying a device-dependent routine in one program and failing to do so in another. Typical

of these routines are those which read positions of the manipulator arm and scale those data for processing. Another similar routine performs the same types of operations with the joysticks.

3.6.3 Spatial Transformations Routines. Resolved motion control and other manual and automatic control algorithms require some facility for translating direction and position vectors expressed in coordinate systems of convenience (e.g., Cartesian coordinates) into the corresponding five-tuples which represent the manipulator joint angles (called "link space" positions or "link space" vectors). Resolved motion control, for example, moves the wrist in terms of Cartesian (X, Y, and Z) work space coordinates, whereas the computer must control the link space angles to move the arm to the commanded location. Other applications, such as resolving force vectors from a wrist-mounted force sensor, require information about the applied forces in other coordinates. In addition to the need for multiple coordinate systems, a particular Cartesian position and orientation of the end-effector may be satisfied by more than one set of manipulator link angles. Thus, the function of some spatial transformation routines is to generate coordinate system conversions which are dependent on the current manipulator angles.

While almost any conceivable coordinate system may assume unique convenience in the description of some particular motion, Perceptronics' experience to date indicates that most control tasks may be expressed easily enough in one or another of only three basic systems:

(1) Manipulator Link Space, in which operations such as "stowage" of the manipulator or deployment of the manipulator to some given physical configuration find a natural expression.

(2) Absolute Cartesian Space, which is the obvious choice for describing the positions of objects in the manipulator work area and linear motions of the manipulator through the work area.

(3) Wrist-Relative Cartesian Space, whose value lies primarily in facilitating interpretation of, and response to, signals from a wrist-mounted sensor.

These primary control coordinate systems are illustrated in Figure 3-15.

While it is possible to convert position specifications directly between any of the above systems with only a single matrix multiplication, Mullen (1973) has shown that computation overhead involved in deriving the conversion matrices is time-consuming to the point of delaying arm motions. For example, the transformation of an end-effector position expressed in absolute Cartesian space into its equivalent link space five-tuple requires evaluating trigonometric functions of the current link positions to produce the elements of an array. This intermediate array must then be inverted to achieve the desired multiplier matrix It is the matrix inversions necessitated by this approach which are so time consuming. Furthermore, there is no particular guarantee that the intermediate array will have an inverse in the first place. This is a direct reflection of the non-uniqueness of link space solutions alluded to above.

To overcome the difficulties associated with the direct transformation technique and its requirements for time-consuming matrix inversion, Perceptronics developed a new and very efficient transformation technique using the wrist position as a reference point. Immediate differential transformations were developed between coordinate systems.

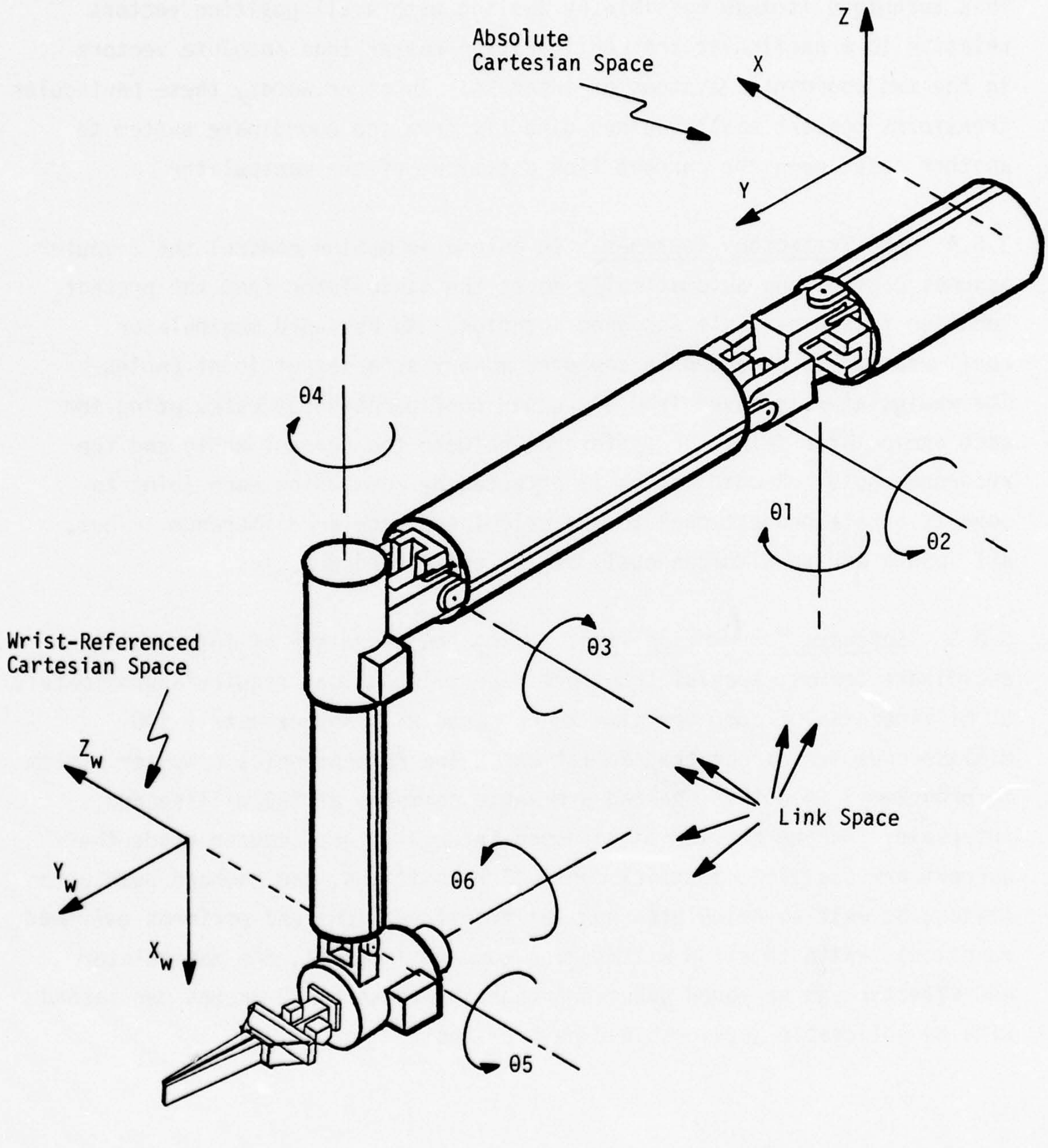

FIGURE 3-15. PRIMARY CONTROL COORDINATE SYSTEMS

This technique is made possible by dealing with small position vectors relative to a particular arm configuration rather than absolute vectors in the two coordinate systems of interest. In other words, these particular transforms convert small vectors directly from one coordinate system to another based upon the current link positions of the manipulator

3.6.4 AMC Trajectory Routines In automatic motion control the computer assumes control and automatically moves the manipulator from the present location to a previously assigned location. An assigned manipulator configuration is recorded in computer memory as a set of joint angles. The manipulator is moved from any other configuration by calculating for each manipulator joint the difference between the current angle and the recorded angle Smooth motion is effected by commanding each joint to move at a rate proportional to the calculated angular difference Thus, all joints arrive simultaneously at the pre-recorded angles.

3.6.5 Software Computation Time. Using the technique of intermediate coordinate frames, spatial transformation calculations require approximately 30 milliseconds of computer time as compared with approximately 500 milliseconds for direct transformations. The Perceptronics computer system is programmed to output updated arm angle commands at 100 millisecond intervals. During the 100 millisecond interval, the computer reads the current arm position, joystick controller positions, and command pushbutton status, as well as calculates spatial transformations and performs overhead functions. With this 100 millisecond command interval, the manipulator end-effector can be moved under RMC mode in excess of 20 inches per second with no noticeable jerkiness and no overshoot.

4. EXPERIMENTAL PROGRAM

4.1 Introduction

The experimental program was divided into training and test phases as shown in Table 4-1. In the training phase the operators practiced basic manipulator skills and the constituent elements of the experimental task. In the test phase, the operators were required to apply the skills they developed during training to perform a simulated maintenance task. The simulated task incorporated all of the elementary training subtasks into a single integrated task with a defined goal. Data was collected during both the training and test phases.

4.2 Test Participants

4.2.1 Characteristics. Ten male operators, students and Perceptronics' employees, served as the test participants for the experiment. The mean age of the test participants was 24 years, and the mean years of education was 14.8 years.

4.2.2 Psychological Testing. Three psychological tests were administered to the participants to permit a preliminary evaluation of the effect of "aptitude" on performance in automated remote manipulation. The three tests were:

(1) Closure Flexibility (Concealed Figures). This test measures the capacity to see a given configuration (diagram, drawing, or figure) which is "hidden" or embedded in a larger, more complex diagram, drawing, or figure.

TABLE 4-1 SUMMARY OF FIRST-YEAR EXPERIMENTAL PROGRAM

PHASE	CRITERION TASKS	CONTROL MODE			
		DIRECT	RESOLVED MOTION	AMC UNASSIGNED	AMC ASSIGNED
TRAINING	RING PLACEMENT	X	X		
	LINE-FOLLOWING	X	X		
	VALVE-TURNING	X	X	X	X
TEST	INTEGRATED MAINTENANCE TASK	X	X	X	X

(2) Differential Aptitude Test (Spatial Relations (Form T)). This test measures the ability to deal with concrete materials through visualization, i.e., to manipulate things mentally, locate in one's mind, and form a plan. This ability is considered necessary in fields where one must visualize objects in three dimensions.

(3) Otis-Lennon Mental Ability Test (Form J). This test measures scholastic aptitude. Emphasis is placed upon measuring the participant's facility in reasoning and in reacting abstractly to verbal, symbolic, and figural test items. The test measures a broad range of cognitive abilities.

These tests were included in the preliminary battery because they measure characteristics likely, on the basis of past findings and experience, to influence successful operation of remote manipulators.

4.3 Training Phase

4.3.1 Test Participant Training. Training was divided into two segments. In Segment 1 the participants received a lecture and demonstration of the structure, function and capabilities of the manipulator system. The purpose was to introduce the participants to the manipulator in general, and to the procedures for manipulator control. In Segment 2 the participants first practiced performing basic manipulation tasks, and later, the constituent elements of the experimental task. The participants received an equal amount of training in all of the alternative control modes (direct, RMC and AMC). Eight to ten hours of practice per participant, conducted in four to five two-hour sessions, were required to complete training.

4.3.2 Training Tasks. During the first hour of training, the participants become familiar with manipulator control characteristics by moving the manipulator in unstructured tasks. After this initial familiarization, all training was conducted on criterion tasks. Performance on these tasks was used to assess learning. The training tasks were:

(1) Ring Placement. This task, illustrated in Figure 4-1, required the participants to pick up metal rings and place them on metal posts. The participants were required to place one small ring (1.5" hole diameter) and one larger ring (2" hole diameter) on a horizontal and a vertical post (.75" diameter). This task was used because it exercised all six manipulator links, and because it involved a variety of basic manipulation elements (i.e., gross movement, fine alignment, grasping and carrying objects, etc.). Participants performed this task under direct control and RMC.

(2) Line Following. This task required the participants to move a 4" plexiglass ring along a 24" long, 1" diameter copper tube, oriented at a 30° angle to the horizontal. This task was used because it required coordinated control of several manipulator joints. Participants practiced this task under direct control and RMC.

(3) Valve Turning. This task required the participants to turn a 2" gate valve a total of 10 one-half revolutions. The valve was mounted at a 45° angle, relative to the manipulator's motion coordinates. The valve turning task was used because it is amenable to preprogrammed movement. Participants performed the valve turning task under (1) direct control, (2) AMC with no points assigned, and (3) AMC with a preassigned point directly over the valve. The following operations are required to perform the valve turning task:

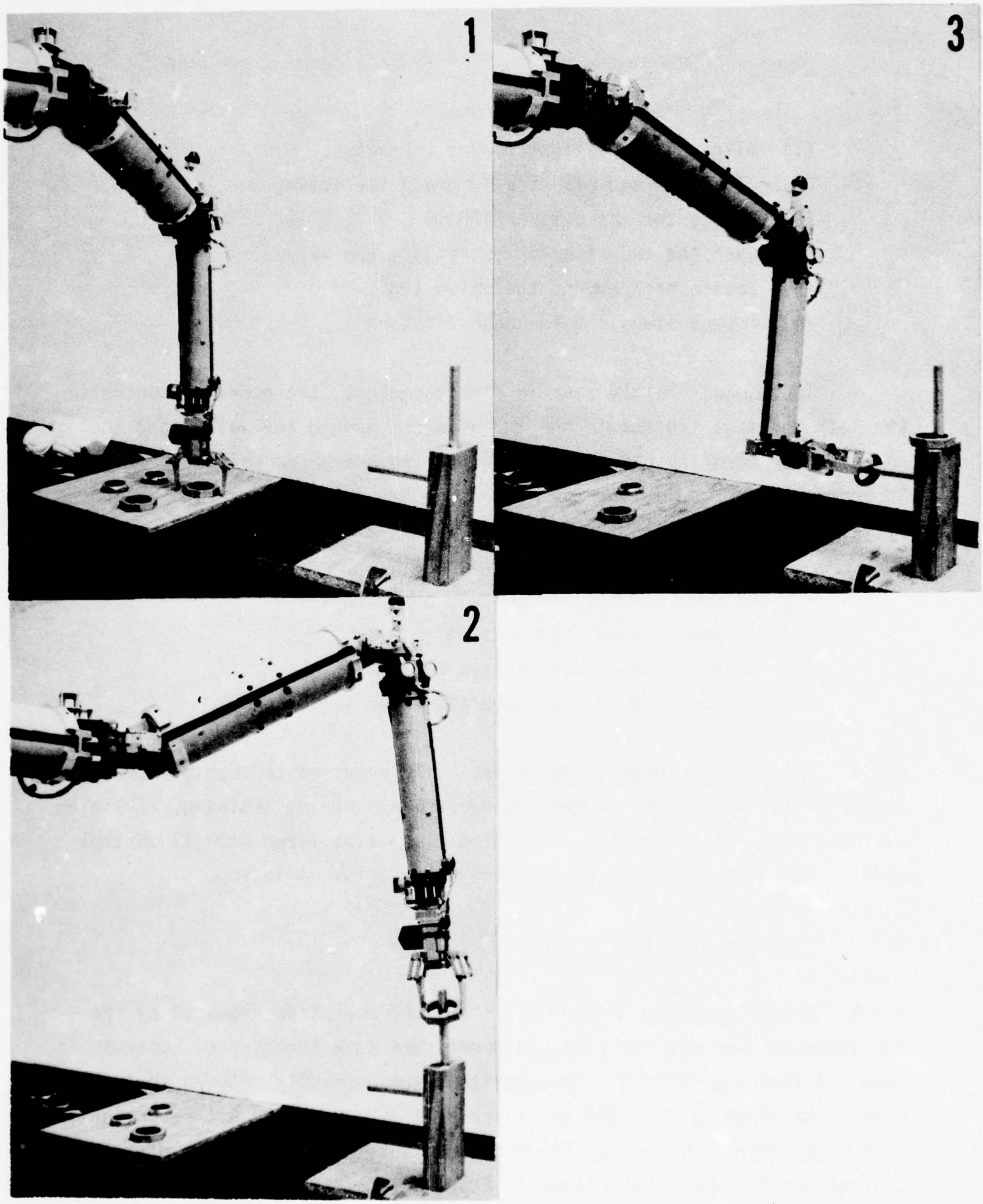

FIGURE 4-1. RING-PLACEMENT TRAINING TASK

(1) Align the end-effector over the valve.

(2) Close the end-effector to grasp the valve.

(3) Rotate the manipulator 180°.

(4) Open the end-effector to release the valve.

(5) Rotate back around the valve 180°.

(6) Repeat steps 1-5 for each 1/2 turn

To accomplish this task in direct control, the operator controls the left joystick (to rotate the end-effector around the valve) and the end-effector open-and-close-toggle switch (to grasp and release the valve). To accomplish the valve turning task using AMC the operator records and cycles through the following points:

(1) Gripper aligned immediately over the valve

(2) Gripper closed around valve.

(3) Gripper closed and rotated 180°

(4) Gripper opened and moved above the valve

4.3.3 Training Performance Measures. Time required to complete the criterion tasks was used to measure performance during training. Training was continued until the task completion times stabilized for all control modes. Stability was indicated by low inter-trial variation.

4.4 Training Results

4.4.1 Ring Placement. Figure 4-2 shows the mean time required by the operators to complete the ring-placement task as a function of control mode and training session The operators substantially reduced their task completion times as training progressed. A 3.8:1 and a 2.9:1 reduction in task completion times was obtained between sessions 1 and 4 for direct control and for RMC, respectively Student's t-tests were performed to

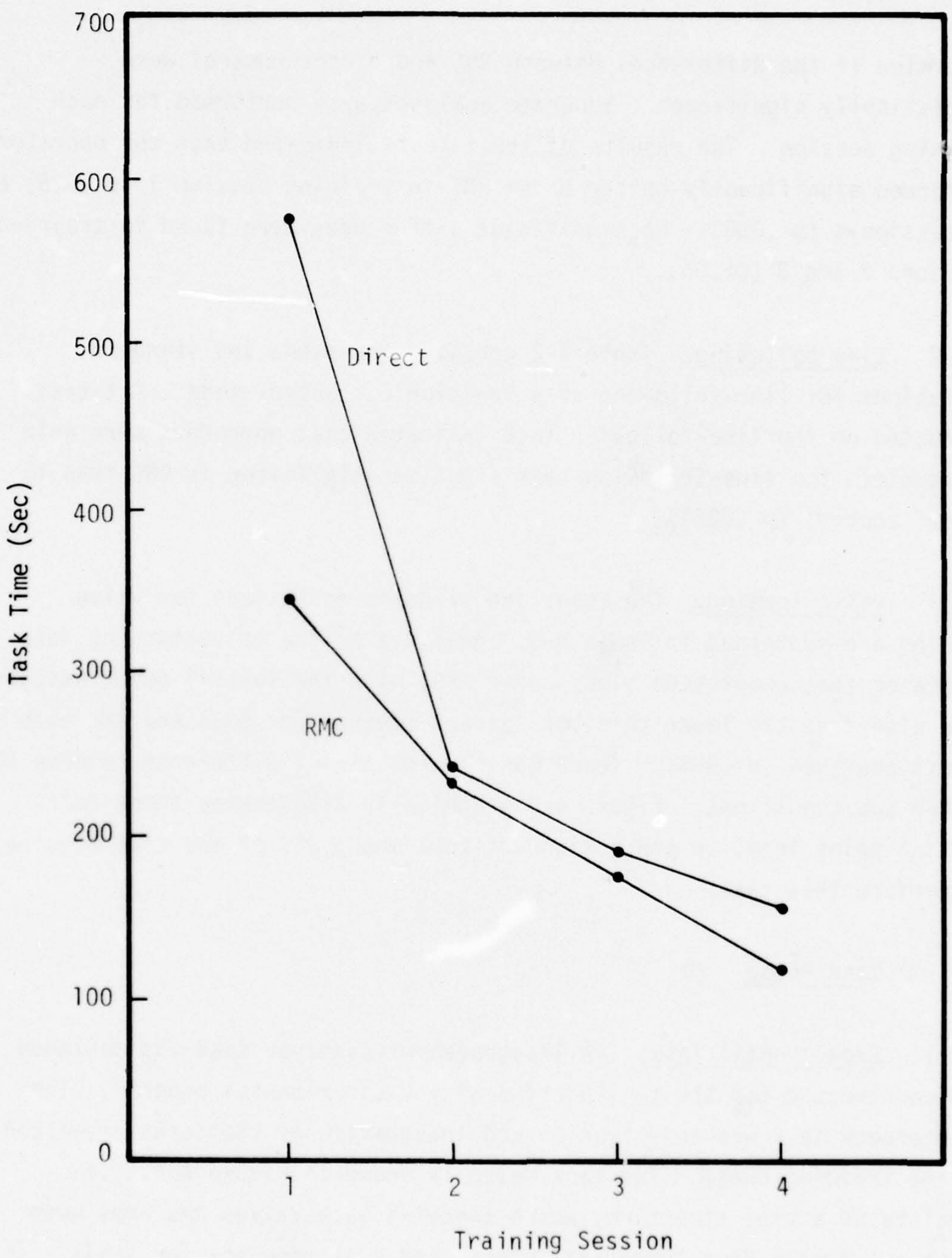

FIGURE 4-2. PERFORMANCE ON RING-MOVING TRAINING TASK AS A FUNCTION OF CONTROL MODE AND SESSION NUMBER

determine if the differences between RMC and direct control were statistically significant. Separate analyses were performed for each training session. The results of the t-tests indicated that the operators performed significantly better under RMC in training session 1 ($p<.025$) and in session 4 ($p<.005$). No significant differences were found in training sessions 2 and 3 ($p>.05$).

4.4.2 Line Following. Table 4-2 contains the means and standard deviations for line-following as a function of control mode. A t-test conducted on the line-following task indicated that operators were able to complete the line-following task significantly faster in RMC than in direct control ($p<.025$).

4.4.3 Valve Turning. The means and standard deviations for valve turning are contained in Table 4-3. Analysis of the valve-turning data indicated that completion times under AMC, with the initial point assigned, were significantly lower than both direct control ($p<.005$) and AMC with no points assigned ($p<.005$). There was no significant difference between the latter two conditions. Figure 4-3 graphically illustrates these data. Initial point location and assignment took about 35% of the time required to perform this task.

4.5 Test Phase

4.5.1 Experimental Task. An integrated maintenance task was designed and constructed for the test portion of the experimental program. The maintenance task was an extension and integration of the tasks practiced in the training phase. The task setup is shown in Figure 4-4. It consists of a pipe structure, which contains gate valves and arms upon which are placed four large seal rings, and a storage box for seals. To complete the maintenance task, the participants were required to:

TABLE 4-2. PERFORMANCE ON LINE-FOLLOWING TRAINING TASK FOR TWO CONTROL CONDITIONS (2-4 TRIALS/SUBJECT)

SUBJECT	DIRECT (SEC)	RMC (SEC)	RMC/DIRECT
1	23.1	19.8	0.86
2	36.2	22.8	0.63
3	56.6	28.6	0.51
4	17.8	14.5	0.81
5	19.1	18.8	0.98
6	18.7	18.1	0.97
7	61.4	43.4	0.71
8	43.2	27.9	0.65
9	14.5	12.6	0.87
10	26.3	31.3	1.19
Mean	31.7	23.8	0.75
S.D.	16.9	9.2	
t Test	$p < .025$		

TABLE 4-3. PERFORMANCE ON VALVE-TURNING TRAINING TASK FOR THREE CONTROL CONDITIONS (2-3 TRIALS/SUBJECT)

SUBJECT	DIRECT (SEC)	AMC UNASSIGNED (SEC)	AMC ASSIGNED (SEC)	AMC(A)/DIRECT
1	183.8	162.0	118.5	0.69
2	175.6	189.1	138.8	0.79
3	165.1	202.9	157.9	0.96
4	192.9	167.4	128.4	0.66
5	151.5	223.0	129.0	0.85
6	282.2	204.6	157.4	0.57
7	264.0	227.4	145.3	0.55
8	217.6	186.5	168.6	0.77
9	186.4	160.1	132.8	0.71
10	283.8	313.9	181.3	0.64
Mean	210.3	203.7	139.8	0.66
S.D.	49.2	45.4	21.4	
t Test		p<.005		
t Test			p<.005	

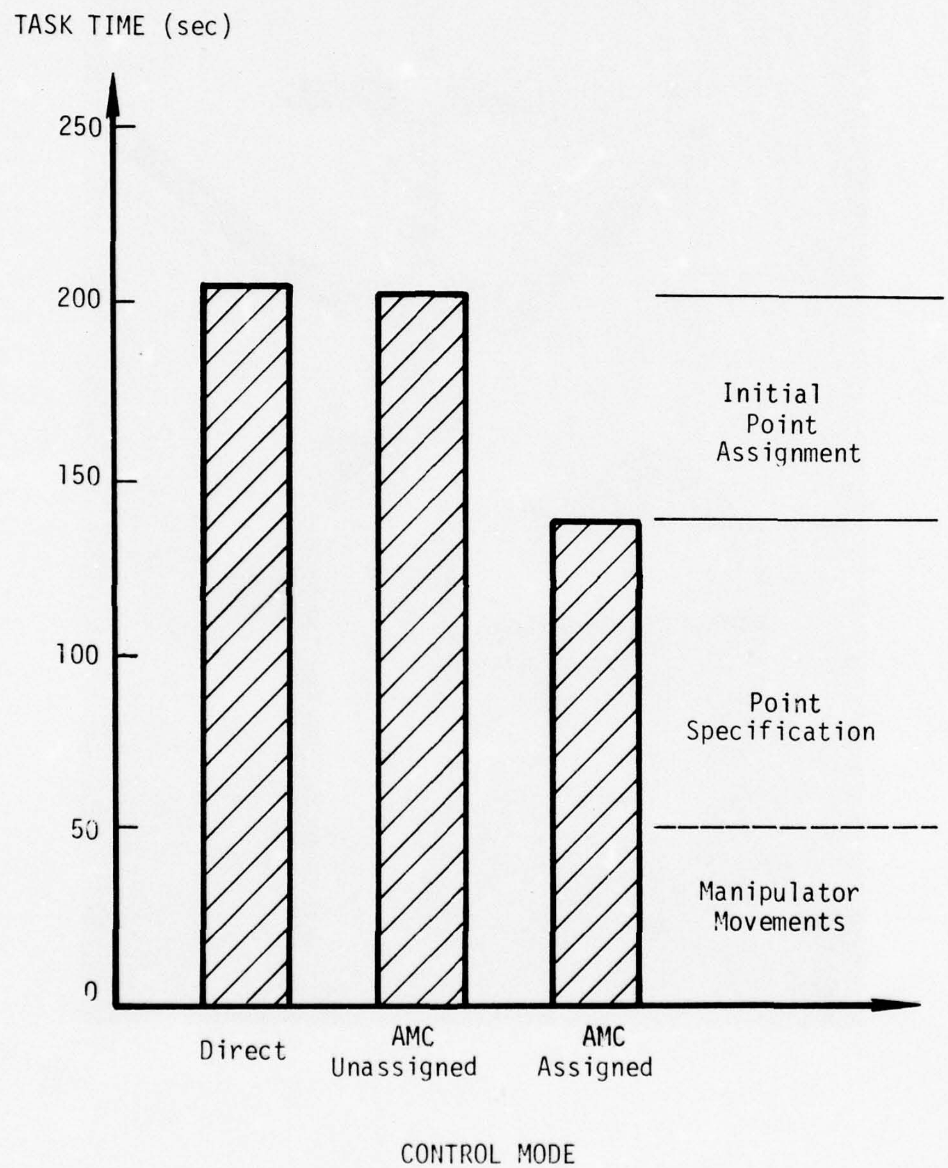

FIGURE 4-3. VALVE-TURNING PERFORMANCE AS A FUNCTION OF THREE CONTROL MODES

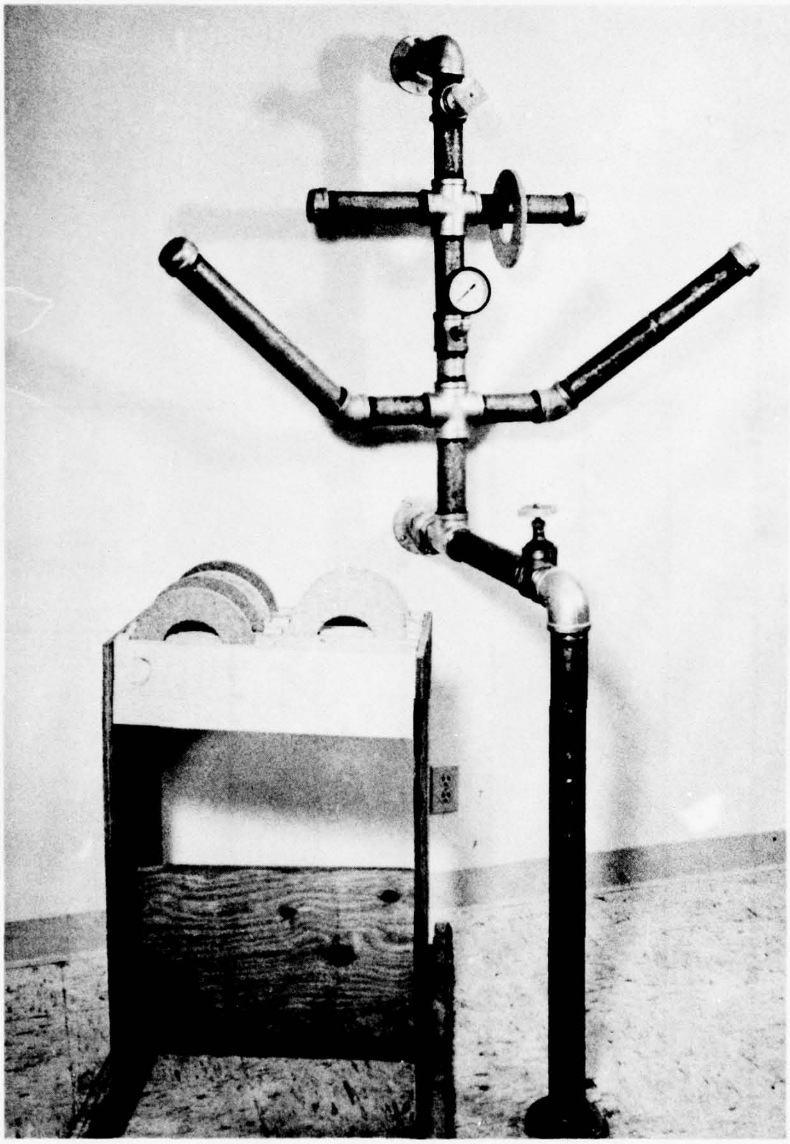

FIGURE 4-4. TASK STRUCTURE AND WORK BOX

(1) Unstow the manipulator
(2) Turn off two valves
(3) Take off the first seal from the pipe structure
(4) Transport the seal and deposit it into one of the empty compartments of the storage box
(5) Pick up one of the replacement seals from the storage box and place it where the seal had been removed
(6) Repeat steps 3 through 5 for each seal to be replaced
(7) Turn on the two valves
(8) Stow the manipulator

The simulated maintenance task includes a representative sample of task elements that are currently performed by Navy manipulators (e.g., configure, orient and position the manipulator in space, operate the end-effector to perform controlled and coordinated dexterous motion and to apply controlled forces and torques, move manipulator to follow a given contour, etc.).

4.5.2 Task Components. For the purpose of analysis the integrated maintenance task was divided into task elements. The major task elements were:

(1) Gross Travel. This element was defined as manipulator movements between two points, around obstacles in tight quarters, and with grasped objects. All of the time required by the operators to maneuver the manipulator between (1) the pipe structure and work box, (2) the extensions of the pipe structure, (3) the two valves, and (4) to stow and unstow the manipulator were recorded separately on the experimental data sheets under gross travel.

(2) Ring Manipulation This element was defined as end-effector movements with elements of positioning, orienting, vertical and horizontal alignment, grasping and releasing objects, etc. Ring manipulation tasks included: (1) removing used rings from the pipe structure, (2) inserting the used rings into the work box, (3) picking up new rings from the work box, and (4) placing the new rings on the pipe structure These task performance times and errors were recorded separately.

(3) Valve Turning Valve turning consisted of aligning the end-effector over the valve, grasping the valve, rotating the valve 180°, releasing the valve, and rotating the end-effector 180° to realign the end-effector over the valve.

4.5.3 Experimental Treatments. Manipulator control mode was the independent variable examined in the present study. Two manipulator control modes were evaluated, augmented and automatic control. Each control mode had two levels. The augmented control levels were unaided, direct control and resolved motion control. The automatic control levels were performance with and without automatic motion control. The following control modes and levels were evaluated:

A. Augmented Control

(1) Direct Control. In unaided direct control each degree-of-freedom of the controller directs a specific joint of the manipulator.

(2) Resolved Motion Control (RMC). In RMC each controller degree-of-freedom controls the movement of the manipulator wrist along an X-Y-Z coordinate axis.

B. Automatic Control

(1) Direct Control Plus Automated Motion Control (AMC). In this mode AMC was available along with direct control. In AMC, the computer automatically moves the manipulator to assignable locations.

(2) RMC Plus AMC. In this mode AMC was available along with RMC.

The four treatment conditions were examined in a 2 x 2 design as follows:

		AUGMENTED CONTROL	
		Direct	RMC
AUTOMATIC CONTROL	No AMC	Direct (A)	RMC (B)
	AMC	Direct + RMC (C)	RMC + AMC (D)

4.5.4 Experimental Design. A treatments-by-subjects experimental design was used to investigate the effects of alternative control techniques on the ability of trained operators to perform remote manipulation tasks. Table 4-4 shows the experimental design. The order of presentation of experimental trials was counterbalanced to avoid confounding task performance with any learning/training that occurred during testing.

4.5.5 Dependent Measures. Performance measurement consisted of task completion times and errors (type and amount) committed by the participants in performing assigned tasks. Performance times and errors were recorded

TABLE 4-4. EXPERIMENTAL DESIGN

	SESSION 1		SESSION 2	
	TRIAL			
SUBJECT	1	2	3	4
1	A	B	C	D
2	B	C	D	A
3	C	D	A	B
4	D	A	B	C
5	D	C	B	A
6	A	D	C	B
7	B	A	D	C
8	C	B	A	D
9	A	B	D	C
10	D	C	A	B

separately for each task element. The following error types were observed and recorded:

(1) Ring Placement Errors. Ring errors were recorded whenever the ring seals dropped from the gripper before the seals had been successfully removed from or placed on the pipe structure, inserted into the work box, or carried between the pipe structure and work box.

(2) Work Box Errors. These errors were recorded whenever the work box was moved during ring seal insertion or removal.

(3) Valve Turning Errors. Several types of errors were recorded during the valve turning task. These included turning the valve in the direction opposite to the intended direction, performing valve-turning operations, in an improper sequence, and activation of inappropriate pushbuttons.

(4) Hazardous Control Errors. These errors were recorded whenever the manipulator impacted the pipe structure or work box.

4.5.6 Experimental Procedures. The pipe structure was installed after all test participants had completed their training. Thus, the participants did not receive any practice performing the experimental task. Prior to the first experimental session the participants read the experimental instructions. The experimenter discussed the instructions with the participants to make sure that they understood what they were required to do. A task list, which listed all of the required tasks in the sequence in which they were to be performed, was taped to the work station adjacent to the controller. The participants were given a pad of paper and a pencil. The experimenter told the participants that they could use the pad and pencil to record the locations of the points they assigned, or in any other way they desired. Before each trial the participants were

given four minutes in which to plan their strategy for accomplishing the simulated maintenance task.

Three of the seven assignable arm locations (points) were pre-assigned in those trials that allowed the operators to use AMC. The three points were assigned prior to the beginning of each trial. A diagram of the point locations (shown in Figure 4-5) was taped onto the work station adjacent to the task list. The operators were instructed to use the four unassigned points (points 1-4) in any manner they desired.

The simulated maintenance task was performed in a continuous manner. The timer was started when the experimenter instructed the participants to begin, and was stopped when the participants had finished all of their assigned tasks. The timer was stopped only if a ring-placement or work box error occurred. Timing continued after the ring had been replaced or the work box relocated. As the participants performed their assigned tasks the experimenter recorded task response times and errors on the experimental data sheet.

4.6 Test Results

4.6.1 Task Completion Time. Table 4-5 presents the time required for each operator to complete the entire experimental task under each of the four control modes. The results of a two-way, within-subject analysis of variance (ANOVA), shown in Table 4-6, indicated that participants performed significantly better under RMC than they did under direct control ($p<.025$). In the summary ANOVA table, the comparison between direct control and RMC is labeled "Augmented Control". The comparison between trials with AMC and trials without AMC is labeled "Automatic Control". No significant main effect was obtained for AMC ($p>.05$) and the two-way interaction (RMC X AMC) was not statistically significant ($p>.05$). To provide a comprehensive

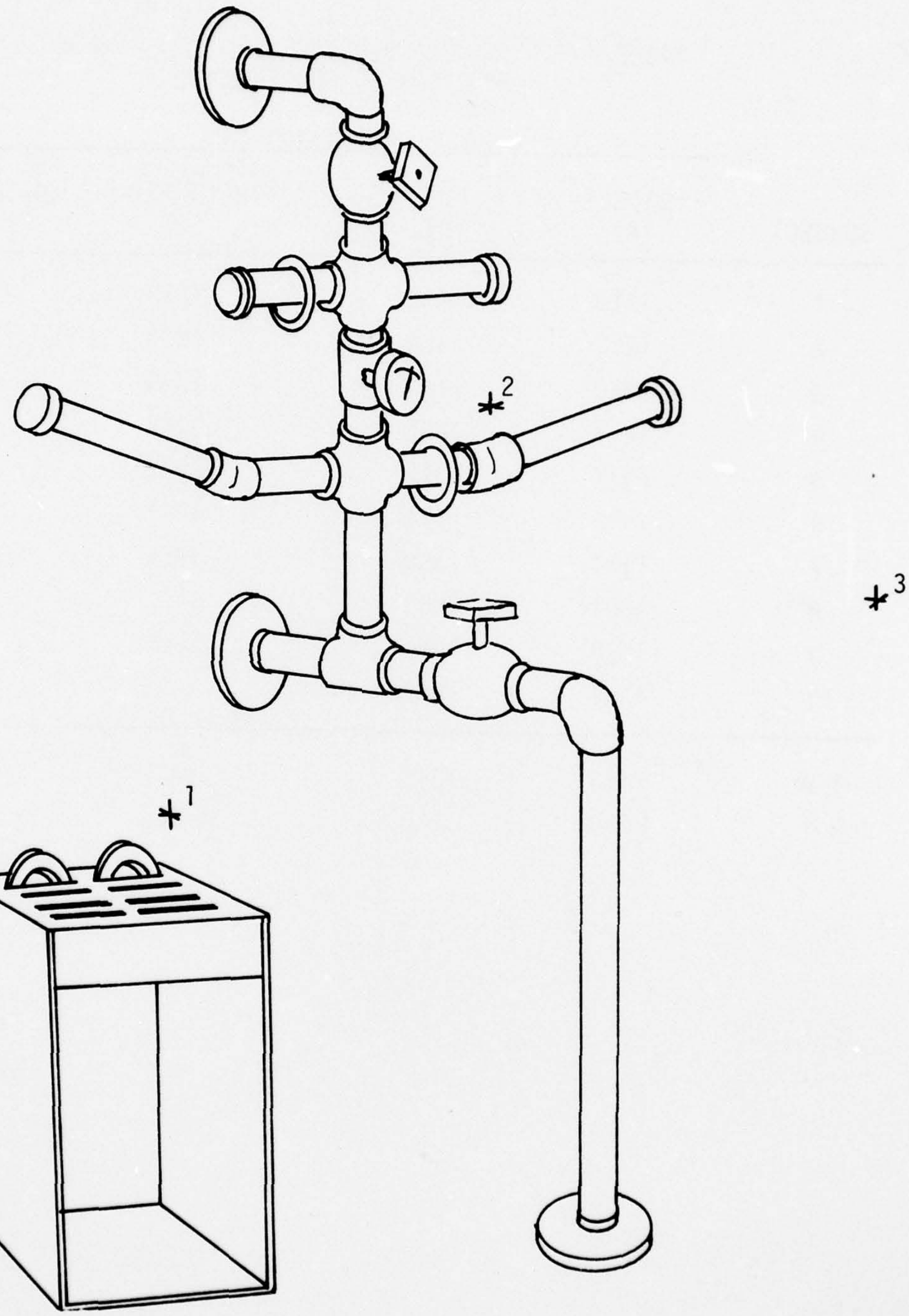

FIGURE 4-5. LOCATION OF ASSIGNED POINTS

TABLE 4-5. TASK COMPLETION TIME (SEC) AS A FUNCTION OF CONTROL MODE

SUBJECT	DIRECT (A)	RMC (B)	DIRECT PLUS GO-TO-POINT (C)	RMC PLUS GO-TO-POINT (D)
	CONDITION			
1	1710	1413	1219	1052
2	1218	1473	1577	1235
3	1420	1185	1590	1124
4	1293	1255	1147	1380
5	1471	1319	1642	1450
6	1840	1474	1381	1443
7	1503	1398	1467	1624
8	1209	1608	1702	1159
9	1390	1014	989	1011
10	1764	1340	1492	1794
Mean	1482	1348	1421	1327
S.D	224	168	234	256

TABLE 4-6. ANALYSIS OF VARIANCE SUMMARY TABLE FOR TASK COMPLETION TIME

SOURCE	df	MS	F
Augmented Control (A)	1	131,446.22	7.87*
Automatic Control (B)	1	16,769.02	.48
Subjects (S)	9		
A X B	1	4,515.63	.07
A X S	9	16,691.61	
B X S	9	34,763.08	
A X B X S	9	64,298.00	
TOTAL	39		

*$p<.025$

description of the contribution of various task elements to the total task completion times, separate analyses were conducted for each major task element.

Gross Travel Time. Table 4-7 contains the time required for each operator to perform the gross travel portions of the experimental task. All control modes produced essentially equivalent times with no significant differences shown between any comparison of control modes ($p>.05$).

Valve Turning Time. Table 4-8 shows participant performance times for valve turning. Analysis of the valve turning data indicated that while task completion times were less with AMC than without it, the difference was not statistically significant ($p>.05$). No significant differences were obtained between direct control and RMC ($p>.05$), and two-way interaction (RMC X AMC) was also not significant ($p>.05$). The valve turning data were further analyzed to determine why AMC did not produce significantly faster performance times. The results of this analysis indicated that a large proportion (70%) of the time required to complete valve turning under AMC was spent in point location and assignment, and in actuating control function buttons.

Ring Manipulation. Operator performance times for ring manipulation are shown in Table 4-9. Analysis of the ring manipulation data, shown in Table 4-10, indicated that participants performed ring manipulation significantly faster under RMC than under direct control ($p<.005$). No significant differences were found for AMC, or for the two way interaction (RMC X AMC) ($p>.05$). Separate analyses were performed on the subtasks comprising ring manipulation. Table 4-11 presents the mean and standard deviations for these tasks as a function of RMC and Direct Control. In three of four of the ring manipulation subtasks (ring insertion, pickup, and placement) the operators performed significantly better under RMC than under

TABLE 4-7. GROSS TRAVEL AS A FUNCTION OF CONTROL MODE

TASK TIME (SEC)

	CONDITION			
SUBJECT	A	B	C	D
1	312	345	282	230
2	233	255	302	331
3	301	275	368	300
4	317	260	220	308
5	241	196	317	262
6	352	301	248	334
7	313	322	296	286
8	210	223	269	221
9	258	259	202	273
10	327	316	212	203
Mean	286	275	272	275
S.D.	47	46	52	46

TABLE 4-8. PARTICIPANT PERFORMANCE ON THE VALVE TURNING TASK AS A FUNCTION OF CONTROL MODE

TASK TIME (SEC)

SUBJECT	CONDITION A	B	C	D
1	736	706	522	497
2	671	765	591	554
3	649	579	578	528
4	630	579	560	787
5	565	657	774	634
6	944	706	712	659
7	595	674	700	762
8	581	941	650	552
9	741	587	490	524
10	817	668	694	868
Mean	693	686	627	637
S.D.	119	109	93	129

TABLE 4-9. MEAN PERFORMANCE TIME ON RING MANIPULATION TASKS AS A FUNCTION OF CONTROL MODE

TASK TIME (SEC)

SUBJECT	CONDITION A	B	C	D
1	662	326	415	325
2	314	453	684	350
3	470	331	644	296
4	346	416	367	285
5	665	466	551	554
6	544	467	421	450
7	595	402	471	576
8	418	444	783	386
9	391	168	297	214
10	620	356	586	723
Mean	503	387	522	416
S.D.	132	91	154	158

TABLE 4-10. ANALYSIS OF VARIANCE SUMMARY TABLE FOR RING MANIPULATION PERFORMANCE TIME

SOURCE	df	MS	F
Augmented Control (A)	1	123,210.00	19.96**
Automatic Control (B)	1	5,953.6	0.55
Subjects (S)	9		
A X B	1	250.00	.01
A X S	9	6,173.06	
B X S	9	10,826.93	
A X B X S	9	23,389.61	
TOTAL	39		

**$p<.005$

TABLE 4-11. MEANS AND STANDARD DEVIATIONS FOR SPECIFIC RING MANIPULATION

	TIME (SECONDS) CONDITION					
	DIRECT		RMC			
TASK	MEAN	S.D.	MEAN	S.D.	RMC/DIRECT	ANOVA
1. Remove Rings From Pipe Structure	94	63	77	65	.82	$p > .05$
2. Insert Rings Into Work Box	91	29	75	24	.82	$p < .005$
3. Pick Up New Rings From Work Box	126	51	76	26	.60	$p < .0005$
4. Place New Rings Onto Pipe Structure	54	27	46	30	.85	$p < .05$

direct control ($p < .05$). In the ring removal task, the operators performed better under RMC, but the difference was not statistically significant ($p > .05$).

4.6.2 Performance Errors. Table 4-12 summarizes the errors committed in performing the integrated maintenance task. As shown, analysis of the performance errors, shown in Table 4-13, indicated that participants made significantly fewer errors with RMC than they committed with direct control ($p < .025$). Approximately 78% of the additional errors committed under direct control occurred in the ring manipulation tasks. The higher error rates for the ring manipulation tasks under direct control were apparently caused by the requirement for controlling more than one degree of freedom. In direct control the operators performed this simultaneous multi-joint control manually; whereas RMC performed multi-joint control automatically. More errors were committed with automatic motion control than without AMC; however, the differences were not statistically significant ($p > .05$). No interaction effect between augmented and automatic control was demonstrated ($p > .05$).

4.6.3 Psychological Test Correlations. Pearson product-moment correlation coefficients were computed to determine the relationship between "aptitude" test scores and the ability of operators to perform the manipulation task. Correlation coefficients were calculated between the three psychological test scores and a composite test score and (1) performance times obtained in the training and test phases of the experimental program, and (2) aiding effectiveness ratios. The composite test score was calculated as the unweighted sum of the three psychological test scores. The aiding effectiveness ratio was calculated as the ratio of performance time with computer aiding to performance time without aiding. Effectiveness ratios were derived for both aiding through RMC in the ring manipulation tasks, and aiding through AMC in the valve turning tasks. The mean times required to complete the four experimental ring manipulation tasks under unaided,

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TABLE 4-12. SUMMARY OF ERROR DATA AS A FUNCTION OF CONTROL MODE (ERROR/TRIAL)

TYPE OF ERROR	CONDITION DIRECT	RMC	DIRECT + AMC	RMC + AMC
Dropped Rings	2.7	1.5	2.9	2.3
Moved Work Box	1.2	0	1.0	.1
Valve Turning Errors	2.7	2.8	3.4	2.4
Hazardous Control Errors	.4	.1	.2	.3
TOTAL	7.0	4.4	7.5	5.1

TABLE 4-13. ANALYSIS OF VARIANCE SUMMARY TABLE FOR PERFORMANCE ERRORS

SOURCE	df	MS	F
Augmented Control (A)	1	62.5	10.42*
Automatic Control (B)	1	2.5	0.25
Subjects (S)	9		
A X B	1	0	0
A X S	9	6.0	
B X S	9	10.0	
A X B X S	9	16.6	
TOTAL	39		

*$p < .025$

direct control and under RMC were used to derive the RMC effectiveness ratio. The AMC ratio was derived by dividing the mean time required to perform the experimental valve turning task without AMC by the mean time to complete the task using AMC. The intercorrelation matrix is shown in Table 4-14. The main findings of the correlational analysis were:

(1) Psychological test scores were not significantly correlated with mean performance time for either the training or experimental tasks ($p>.05$).

(2) High positive correlations were obtained between the psychological test scores and the two effectiveness ratios. Specifically, those participants who scored high on closure flexibility and the composite test score also demonstrated relatively better performance with both RMC and AMC, compared to unaided control. Participants with high Differential Aptitude test scores performed relatively better with RMC.

4.6.4 Learning Effects. An analysis of variance was conducted to determine whether the participants demonstrated any significant learning during the study. The results of this analysis indicated that the participar were able to complete the simulated maintenance task significantly faster as the experiment progressed. A 21% reduction in task completion times were obtained between Trial 1 and Trial 4 ($p<.001$). Figure 4-6 shows the mean time required to perform the simulated maintenance task, and each of the major task elements as a function of experimental trial. As can be seen in this figure, the greatest amount of learning occurred in valve turning and ring manipulation tasks. Approximately 87% of the reduction in total task completion time was due to improvements in these two tasks, made up of 43% and 44% improvement in valve turning and ring manipulation, respectively. Only a 13% reduction in gross travel time was obtained between Trials 1 and 4.

TABLE 4-14. CORRELATION MATRIX FOR PSYCHOLOGICAL TEST SCORES AND MANIPULATOR PERFORMANCE

		PSYCHOLOGICAL TEST SCORES			
		CLOSURE FLEXIBILITY	DAT	OTIS LENNON	COMPOSITE
Psychological Test Scores	Closure Flexibility	1.0	.42	.08	.91**
	DAT	--	1.0	.41	74**
	Otis Lennon	--	--	1.0	.36
	Composite	--	--	--	1 0
Performance Scores	Task Completion	12	-.42	- 31	-.11
	Gross Travel	.18	-.31	- 42	- 04
	Ring Manipulation	.01	-.18	-.18	-.08
	Valve Turning	.18	-.39	- 28	-.12
	Ring Placement	52	.04	- 20	.37
	Line Following	-.34	-.26	- 07	- 36
Performance Ratio Scores	RMC Effectiveness	.60*	.73*	29	76**
	AMC Effectiveness	.63*	.50	24	69*

* $p < .05$
** $p < .01$

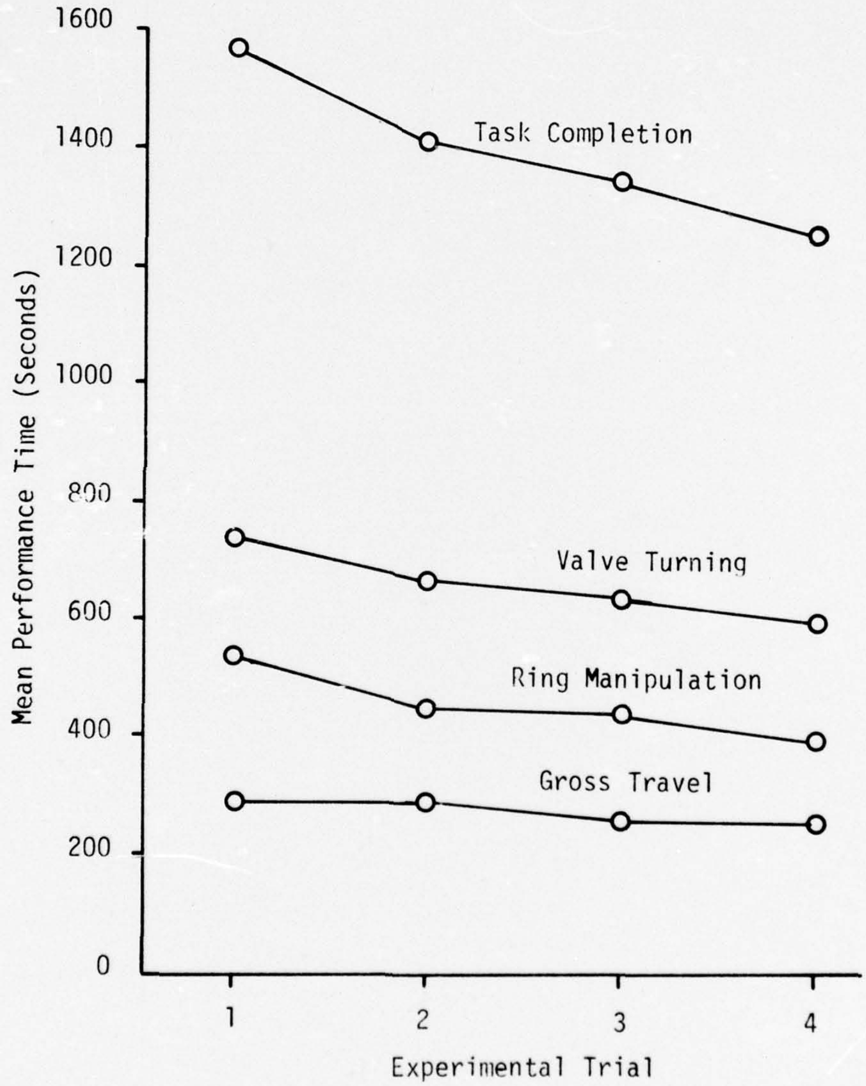

FIGURE 4-6. MEAN PERFORMANCE TIME FOR TOTAL TASK COMPLETION AND MAJOR SUBTASKS AS A FUNCTION OF EXPERIMENTAL TRIAL

5. DISCUSSION AND CONCLUSIONS

5.1 General

The focus of this first year's experimental program was to determine the initial relationships between major communication variables and manipulator system performance. The experimental studies have evaluated the performance of a number of operators who used two forms of augmented computer control to perform a wide variety of complex tasks. The range of tasks examined, the integration of the tasks into a single task, and the number of operators observed, provided a unique opportunity to evaluate performance with a computer-aided remote manipulator in extended and changing conditions. The results of these studies indicate in preliminary fashion the performance improvements to be gained with computer-assistance techniques, the tasks to which computer-aided control can be best applied, and the critical role of the man-machine interface in effective utilization of computer-assistance. The results also suggest the potential benefits of computer-aiding to operator training and indicate that a test battery might be used to select operators who will be able to use computer-aided control most advantageously.

5.2 Computer-Augmented Control

Results of the experimental studies show that augmented and automated manipulator control can significantly improve an operator's performance with a remote manipulator. Augmented control, in the form of simple resolved motion control of the wrist joint, almost universally reduces task performance times and error rates as compared with unaided manual control. This performance improvement is particularly high for tasks requiring fine, dexterous control and simultaneous, multi-joint

control Such tasks are characterized by manipulator movement near or with respect to objects in the work environment These tasks are illustrated by the line-following task in the training phase and the ring manipulation tasks used in the training and test phases of the experimental program The experimental results showed that operators demonstrated a 22% improvement in mean performance time and a 34% reduction in mean error rate for ring manipulation tasks with resolved motion control Similarly, a 25% improvement in mean performance time was demonstrated with resolved motion control in the line-following tasks. However, no significant performance improvement was demonstrated for gross travel. These findings indicate that resolved motion control, of even the simple form of X, Y, and Z control of the wrist point, will improve performance in tasks requiring coordinated manipulator motion along work space dimensions Furthermore, performance of tasks that do not require coordinated multi-joint control are not impaired by using RMC

These results are in agreement with the findings of Mullen (1973), who demonstrated the general superiority of resolved motion rate control when a hand controller (as opposed to on-off buttons) are used However, the larger number of operators used in the present study permitted a statistical test of the differences between control modes. Interestingly, Mullen's data show the improvement in performance with a resolved motion control to occur with transport segments of tasks, as opposed to the positioning and alignment portions. The present data show no improvement during gross travel tasks. This difference may be due to the differences in the two methods of resolved motion control. The origin of the coordinate system was at the tip of the end effector in Mullen's system, thus involving end-effector orientation as well as location. The origin of the RMC coordinates was located at the wrist joint in the present system, thus involving only wrist location.

Regardless of the differences in tasks most benefitted by RMC, these data strongly support the notion that resolved motion control allows an operator "to concentrate more on the task and less on the operation of the manipulator (Mullen, 1973, p. 10)." To move the end point along some dimension in the work space, the operator need only move the hand controller in a similar direction; whereas with a non-aided controller the operator must make complex, multi-dimensional transformations to move the end point.

5.3 Automatic Control

Automatic motion control also demonstrated potential usefulness in improving performance of manipulation tasks that must be repeated many times. AMC reduced performance time for valve turning in the training and test phases. Time improvements were particularly dramatic when the initial location over the valve was preassigned. However, the effectiveness of automatic movement from one location to another is dependent on the task characteristics and the method of invoking AMC. Automatic motion control is useful for tasks which must be repeated many times. Even in tasks with only a few repetitions, AMC can also be useful when the time required to invoke it is minimal compared to the total time required for one repetition.

The time required to invoke the automatic function must be short compared to the time required to manually perform the task. For example, to perform the valve-turning task in the present studies, the operator had to depress 13 function buttons in the proper sequence to complete one automatic cycle. This not only induced many errors, but also consumed much time. Analysis of the valve turning time indicated that approximately 70% of task time was consumed by initial point definition and button pushing. Actual manipulator motion time under AMC was only 27% of the motion time required with manual control. This demonstrates the dramatic improvement in performance time that can be expected if the procedure for

invoking automated control is properly designed It also suggests that the approach to increased improvement should involve (1) linking elemental automatic operations so that one command leads to a number of manipulation steps, for example, one or more valve turning sequences; and (2) giving the computer the capability to adapt to the actual work conditions, so that the operator is relieved of the responsibility for precise location, alignment, etc.

5.4 Utilization of Computer-Assistance

The results of the present studies not only indicate that performance in selected tasks is improved by using computer assistance, but also indicates that operators vary in their ability to effectively use the control assistance Moreover, these initial test results suggest that an operator's ability to use computer assistance in remote manipulation can be tested with a selected test battery. Test results with the limited number of subjects (10) demonstrated that the operator's relative performance with computer assistance, as compared with non-aided control, was significantly correlated with test battery results. This tentatively suggests that the test battery can be used to select operators who will benefit by computer assistance function High scores on the test battery do not predict better overall performance with computer-aided control in comparison to performance with unaided control. Further studies with additional operators and a more extensive test battery that includes measures of manual dexterity, mechanical comprehension, etc., will be required to confirm the usefulness of a test battery as a potential operator-selection device.

5.5 Integration of Man-Machine Interface

The experimental studies were not only an evaluation of modes of computer assistance in manipulator control, but also an evaluation

of procedures for selecting and monitoring the control modes. The results of the experimental studies clearly illustrated the critical role of the man-machine interface in computer-aided remote manipulation. For computer-assistance functions to be most effective in improving performance, the operator must be able to invoke the functions in a simple, readily-understandable and expedient manner. The computer-assistance functions that can be selected with only a few actions, requiring little time, will be effectively used and can be expected to improve performance in the appropriate tasks. However, computer-assistance functions either will not be utilized or will be used with increased errors or performance times if those functions can be selected only (1) with many actions, (2) with actions that must be executed in a specific sequence, or (3) with actions that consume much time. Similarly, functions that are readily distinguishable, and whose status is clearly displayed will be effectively used; whereas those functions that are not readily monitored will be improperly selected or will be used with increased errors.

As described previously, the present control console consists of a pair of joysticks plus an array of function pushbuttons, with indicator lamps located in the pushbuttons. An operator selects the various computer assistance functions by pressing one or more pushbuttons. The lamps indicate which function is currently in effect. The experimental results indicate that few errors were committed when operators chose those functions that could be selected by a single pushbutton. These functions included direct control, resolved motion control, and the four rates of motion. However, errors were committed when the operators chose functions which could be selected only by pushing several buttons. For example, AMC was selected by pushing the Go-To-Point button, followed by the number buttons. To use AMC to accomplish the valve turning task, the sequence of Go-To-Point and number buttons had to be repeated many times in succession, with the number changing at each step. This sequence

produced many errors, including buttons pressed out of sequence, and confusion between Go-To-Point and Record-Point.

Additional errors were caused by the method provided for entering numbers. Rather than a decimal number keyboard, binary number pushbuttons (4_2, 2_2, 1_2) were provided. Not only did this require a translation from the more familiar decimal system, but also necessitated multiple button pushes, such as pushbuttons 4_2 and 2_2 to specify location 6_{10}.

The requirement for multiple actions to accomplish a single task, as in the valve-turning task, also highlighted the need for adequate feedback of the status of operations and for prompting of the next required step. The indicator lamps showed which pushbuttons had just been activated, thereby indicating the present status of the manipulator control. However, no provision was made to inform the operator of the next required step in an ordered series of steps. For example, to perform one repetition of valve-turning, an operator would use AMC to move to four locations in sequence. Operators made many sequence errors in this mode and stated that they could not remember which location was next in sequence.

For several tasks, visual feedback alone is not sufficient to reliably complete the task, particularly under automatic motion control. The present experiment demonstrated that some form of force sensing is required to supplement visual feedback. On a number of occasions when the manipulator was in contact with work objects, hazardous control errors would occur. Such errors were characterized by sudden, gross arm movements which frequently resulted in violent contact of the arm with a nearby object. While some hazardous control errors could be attributed to control reversals by the operator, many occurred when the arm had applied an excessive force to an object and then slipped off and moved in the direction of the force being applied. No force information was available either

to the operator or to the computer, thus the operator relied solely on visual and auditory cues to estimate any applied forces. Similarly, tasks requiring fine, controlled application of forces and torques, such as valve-turning, were slower than would be expected if force feedback were available.

In addition to the function-selection pushbuttons, the present operator console includes a pair of rate-control joysticks. Data reported by Mullen (1973) suggest that a master-slave controller demonstrates generally superior performance over a rate controller or a resolved motion rate controller. However, a master-slave controller can be potentially difficult to integrate with automatic motion functions. As suggested by McGovern (1974), control transfer from the master-slave controller to AMC functions is straightforward and can even occur automatically. However, the transfer between automatic control to the master-slave controller is more difficult if the physical registration between the master and slave is to be retained. No such registration is required for a rate controller.

Although several hours of training were required before the operators were proficient with the rate-control joysticks, the operators experienced little difficulty in using these analog control devices following training. Indeed, for the level of automation available in the current system, the tasks would have been impossible to control without some form of manual controllers. This reinforces the idea (McGovern, 1974) that a combination of command types, both analog and symbolic, will be most useful if they facilitate manual control. Thus, a general rule of thumb for designing computer-assistance functions and for designing and implementing the command language for controlling these functions would be that "the computer-assistance function must be easier or faster to use than to do the task manually."

From the experience with the present interface and from the experimental results, several preliminary guidelines can be given for the design and integration of a communications interface for multi-moded supervisory control of a manipulator:

(1) When a variety of tasks are to be performed, performance will be improved if the operator has a variety of computer-aided and non-aided control modes from which to choose.

(2) When multiple control modes are available, the operator should be able to transition smoothly among the modes, choosing them as the task demands require them.

(3) Both analog and symbolic commands will be required when automatic functions and manual control are combined.

(4) Selection of any control function should be as simple as possible involving:

   (a) A single command to request a control function
   (b) One command that initiates a unitary element such as one complete revolution in valve-turning
   (c) A minimum of time or effort to select the command
   (d) Automatic selection where feasible.

(5) When actions must be performed in sequence, automatic functions should be able to independently cycle through the complete sequence or the interface should prompt the operator with the next required step

(6) Visual feedback alone may not be sufficient to control a manipulator in contact with work objects. Force feedback can be used to supplement visual feedback, giving information about the forces being applied, in addition to the information that contact has been made. When force sensing is provided, the force information can be displayed to the operator, used by the computer to guide or stop the manipulator, or both.

5.6 Computer-Aiding in Training

The results of the present studies suggest that computer-aided control can be used to improve operator performance early in training. This is indicated by the significantly lower performance times with resolved motion control in the first session of training. Operators using RMC required 40% less time than when using non-aided control in the first training session. Although not tested in these experimental studies, the lower initial performance times suggest that computer-aided control could decrease the training time required to reach criterion performance.

It has been suggested (Mullen, 1973; Zadaca, Lyman, and Freedy, 1974) that resolved motion rate control is more natural to an operator than is conventional rate control, since RMC involves movement in natural arm coordinates such as sweep, reach, turn, lift, etc. Thus, an operator who is learning to control a manipulator could be expected to demonstrate better performance early in training. With RMC, the operator must still learn the dynamics of the manipulator movements and the control/arm relationships. However, he does not also have to learn the complex joint-by-joint transformations of non-aided rate control. This same argument also suggests that an operator would be better able to transfer to a new task with resolved motion control. However, the experimental studies in this year's program were not designed to test the relative transfer performance under the available control modes.

5.7 Operator Training and Motivation

Analysis of the data from the training phase and the learning effects in the test phase indicates that remote manipulator control is a relatively difficult skill to learn and that many hours of training are required for proficiency. The operators were given 10 hours of training prior to the testing phase and were showing additional improvement after the additional four to six hours in the test The selected operators were initially inexperienced in controlling manipulators or similar remotely-controlled machines, thus necessitating a training program which started with elementary movements and progressing to coordinated movements and manipulation of objects. The inexperienced operators are representative of such potential users as scientists or technicians who must be trained to use a manipulator system for a specific task involving primarily their scientific or technical expertise The amount of time required for training in the present studies suggests that a significant advantage can be gained if computer assistance functions can reduce training time or improve in-training performance

Despite the length of time spent in training and the test phases, the operators appeared to be highly motivated throughout the studies They expressed no boredom with the tasks and showed eagerness to know how their performance compared with other operators. This contrasts with other studies (Mullen, 1973) which noted boredom on the part of test participants. Several characteristics of the present task apparently contributed to the operator's motivation to perform well. The task used in the present study included a variety of subtasks, all of which were performed in sequence to complete the overall task This integration of many subtasks provided an opportunity to perform different operations without immediate repetition. The overall task gave each subtask a meaningful relationship to the other subtasks, as well as toward an overall goal. The goal of the overall

mission was also well defined which allowed the operator to judge the adequacy of his own performance. The task was also sufficiently long (15 to 30 minutes) to allow the operator to plan a strategy and to be able to trade off performance in one subtask for another. Finally, the operators apparently perceived competition among themselves and were eager to know how well they were doing. While no competition was intended, each operator's performance was constantly observed and timed, giving an impression of evaluation in comparison with all others.

5.8 Conclusions and Future Directions

5.8.1 Conclusion. In summary, the theoretical analysis and experimental results provided a good initial look at computer assisted control functions and communications with a computer-aided manipulator in a varied environment. The use of a multifaceted task gave us a chance to observe the performance advantages of various computer aiding functions in a situation resembling real-world operations. Further, a sufficient number of operators were used to permit statistical tests of observed performance differences. The data obtained in the experimental studies lead to the following conclusions:

(1) Resolved motion control of even the simple control of the wrist point can significantly decrease performance times and reduce errors in selected manipulation tasks.

(2) Automatic motion control in the form of automatic movement to specific locations can potentially improve performance of repetitive tasks if the AMC includes sufficiently numerous and self-guided actions.

(3) Higher-level aiding schemes require careful design and evaluation of the communications language and the man-machine interface to allow naturalness, understandability, and expedience in controlling a manipulator.

(4) A test battery, including the Differential Aptitude, Spatial Relations and Embedded-Figures tests, can potentially be used to predict operators who will derive the most benefit from computer-aided control techniques

(5) Computer assisted control can potentially be used to improve operator performance early in training.

The results of the present efforts also served to focus attention on the communications needs of adaptive aiding in remote manipulation. Adaptive aiding, as we define it, involves two major features Sensory feedback to the computer regarding completion or non-completion of automatic task elements, and linking of separate task elements to form larger goal-directed tasks Our subsequent work will move toward implementation and evaluation of adaptive aiding functions and the command language structure which can be used to control such automated functions.

5 8 2 <u>Future Directions</u>. Major objectives for subsequent research include the following:

(1) Continue the theoretical analysis to investigate the structure and mechanism of higher-order command languages and to specify communications requirements and techniques

(2) Modify the computer-controlled manipulator system to incorporate (a) the capability to provide sensor feedback to the computer and the operator, (b) the capability to chain automatic commands, and (c) a man-machine interface designed to support adaptive aiding.

(3) Perform a series of experimental studies to examine man-machine performance with adaptive computer-aided manipulation using chained and non-chained commands.

(4) Identify major factors influencing the success of man-machine communications modes and media, and suggest initial guidelines for design of communication and training procedures in remotely-manned systems.

The overall objectives are to identify through theoretical analyses the critical factors in communication with a computer-aided manipulator, to determine through an experimental program the relationships between these communication factors and system performance, and to develop guidelines for designing and implementing communication procedures for selecting and controlling computer-aided manipulators in real-world tasks.

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